Vol. XCIII. No. 2. March–April, 1956

GEOLOGICAL MAGAZINE

Edited by

O. M. B. BULMAN, S. R. NOCKOLDS, and W. B. HARLAND

assisted by

PROFESSOR W. G. FEARNSIDES PROFESSOR O. T. JONES
PROFESSOR LEONARD HAWKES PROFESSOR W. J. PUGH
PROFESSOR C. E. TILLEY

CONTENTS

PAGE

BATTEY, M. H. The Petrogenesis of a Spilitic Rock Series from New Zealand 89

HARLAND, W. B. Tectonic Facies, Orientation, Sequence, Style, and Date 111

OLIVER, R. L. The Origin of Garnets in the Borrowdale Volcanic Series and Associated Rocks, English Lake District 121

DANIELS, J. L. The Petrology of the Pre-Cambrian Rocks of the Southern Portion of Southampton Island 140

DAVIES, R. G. The Pen-y-gader Dolerite and its Metasomatic Effects on the Llyn-y-gader Sediments 153

HOPKINS, W. *Neoglyphioceras* cf. *spirale* (Phillips) from Ingleborough 173

EYLES, J. M. Fausto de Elhuyar (1755–1833), A Spanish Mining Geologist 175

CORRESPONDENCE

The Palaeozoic Coral Genera *Depasophyllum* Yü and *Depasophyllum* Grabau 181

Tillite-Granite Transformations 181

REVIEWS

pp. 182–4

STEPHEN AUSTIN & SONS, LTD.
CAXTON HILL, WARE ROAD, HERTFORD, HERTS

SUBSCRIPTION 40/- PER ANNUM

GEOLOGICAL MAGAZINE

founded in 1864

by the late Dr. H. Woodward, F.R.S., with which

is incorporated

THE GEOLOGIST

(founded 1858)

Published every two months, price 40/- per annum
(single numbers, 8/6).

Subscriptions for 1955, inquiries relating to back stock, advertising, etc., should be sent to Stephen Austin & Sons, Ltd., Caxton Hill, Ware Road, Hertford, Herts.

The Editors are directed to make it known to the public that the authors alone are responsible for the facts and opinions contained in their respective papers and for the correctness of their references.

Instructions to Contributors.

Articles submitted for publication in the *Geological Magazine* should be addressed to the Editors at the *Sedgwick Museum, Cambridge*, not to the Publishers.

Manuscripts should be typewritten, double-spaced, and preferably with a wide margin, and should be carefully revised; they should be as concise as possible and should not exceed 10,000 words. In the case of a long article allowance must be made for text-figures at the rate of approximately twenty words per sq. in. MS. must be accompanied by a short abstract, 50–100 words. References should not be given in footnotes, but arranged in alphabetic order of author's names at the end of the article; the author's name should be followed by date of publication, and the title of each paper should be given in addition to volume and page numbers of the Journal, thus:—

LAPWORTH, C. 1878. The Moffat Series. *Quart. Journ. Geol. Soc.*, xxxiv, 240–343.

References should be cited in the text by author's name and date, with page reference if necessary, in brackets:—(Lapworth, 1878, p. 339).

Illustrations should be so drawn as to allow reduction to a maximum size of $6\frac{1}{2} \times 3\frac{1}{4}$ inches (the type-area of the Magazine) and originals must not exceed 40 × 22 inches. Map lettering should be such as to be clearly legible after reduction (equivalent to 5-point as a *minimum* on reduction), while lettering on text-figures should in general be left in pencil for printing.

Authors will receive 25 reprints free of cost.

GEOLOGICAL MAGAZINE

VOL. XCIII. No. 2. MARCH-APRIL, 1956

Issued 24th May, 1956

The Petrogenesis of a Spilitic Rock Series from New Zealand.

By M. H. BATTEY

(PLATE V)

ABSTRACT

Well-preserved examples of spilites show marked affinities with certain tholeiites in texture, chemistry, differentiation trend, and in some aspects of their mineralogy. The presence in them of albite and apparently primary chlorite, in association with unaltered augite, is ascribed to the influence of water as a component of the magma, and the high content of alkali in the basic members to retention of volatile oxides present in tholeiitic magma. Evidence is lacking of large-scale metasomatism by external agencies and the postulate of a special primary magma seems unwarranted. A series may be traced, in rocks of different environments, from "dry tholeiite" to "wet tholeiite" to spilite.

Four new rock analyses and one of chlorite are given.

INTRODUCTION

THE rocks to be described in this paper come from three localities in the north of the North Island of New Zealand, namely the north side of Doubtless Bay, Mount Camel, and Great Island in the Three Kings Group. In these three areas spilitic lavas, sometimes with pillow structure, occur in association with keratophyres and interbedded marine sediments of the greywacke facies. Members of the group were described from Great Island by Bartrum (1936) and descriptions of their field relationships have been given by Battey (1950, 1951).

In past discussions of the spilite problem the rocks described have often been subjected to some degree of regional metamorphism and this has tended to obscure, more or less, the characteristics of the lavas (cf. Turner and Verhoogen, 1951, p. 203). Amongst the northern New Zealand rocks there are excellent examples of apparently unmetamorphosed spilites, as well as of those which have undergone a moderate degree of thermal metamorphism. The unmetamorphosed types provide favourable material for petrographic and chemical study of the series through a fairly complete range of decreasing basicity, which

links up with keratophyric types the petrographic and chemical features of which have already been described (Battey, 1955).

Petrography

The unmetamorphosed spilites consist principally of albite, pyroxene, chlorite and iron ore with a small amount of quartz, minor apatite and sometimes a little potash feldspar, prehnite, epidote, pumpellyite or calcite.

The albite is always the low temperature form and is, in general, quite fresh in appearance, contrasting strongly in this respect with the feldspar in the amphibolized (thermally metamorphosed) spilites found in the aureole of a later gabbro-diorite intrusion. One rock only has been noted, amongst types remote from these thermal effects, in which the albite is at all heavily mottled with prehnite inclusions (6223).[1]

In spilites possessing intersertal or variolitic texture curved growth forms of albite are common, while forked and hollow microlites are seen in all types, and in some cases delicate plumose outgrowths of feldspar spring from the tips of the microlites. The preservation of these structures suggests that no volume changes, such as might accompany metasomatism, have affected the rock since the crystals grew.

The hollow microlites often enclose chlorite or obscure groundmass material, but there is no support for the view expressed by Sundius (1915, p. 47) that the feldspar is altering to chlorite, a suggestion that involves profound compositional changes. Chlorite flecks sometimes present in the feldspar must be regarded as inclusions or the alteration product of inclusions.

The pyroxene may take the form of anhedral plates, short prisms, long, curving fasciculate or branching prisms, so slender at times as to be almost threads, granules or margaritic dots. One case was noted of graphic intergrowth between pyroxene and albite (cf. Scott, 1951a), and subophitic relationships of these two minerals are also to be observed.

The pyroxene is faintly brown in colour [2] but without perceptible pleochroism. The use of Hess's (1949) curves for β and 2V shows that

[1] Numbers refer to Geological Catalogue of Auckland Museum. A representative series of the rocks is lodged in the Department of Mineralogy and Petrology of Cambridge University.

[2] The pyroxene alters by incipient weathering to orange-brown pseudomorphs of high birefringence. The resulting prisms are exactly comparable with the material described by de Roever (1942, pp. 233, 236, Pl. IV, 1) as iddingsite pseudomorphs of olivine in spilite and poenite from Timor. The regular intergrowths with rods and plates of titaniferous ore he describes are a characteristic feature of the pyroxene of spilites. From comparison of slices of poenites with the New Zealand rocks it seems likely that the Timor mineral was pyroxene also.

the pyroxene is a common augite with composition ranging from $Ca_{41}Mg_{38}Fe_{21}$ to $Ca_{36}Mg_{35}Fe_{29}$ atomic per cent. Measurements in eight thin sections gave the following average values:

β 1·698 (8 measures, range 1·691–1·707)
$2V\gamma$ 47° (20 measures, range 45°–55½°)
Z : c 42°–45°

Other records of the optical properties of pyroxenes in spilites are given in Table 1.

Only one type of pyroxene was observed in the New Zealand rocks [1] and this is in accord with the finding of Benson (1915, p. 141) who detected no pigeonitic pyroxene in his Nundle spilites, in spite of special search.

TABLE 1.—OPTICAL PROPERTIES OF CLINOPYROXENE FROM SPILITES

Rock	Locality	2V	Z:c	R.I.	Notes
1. Spilite	Nundle, N.S.W.	42°–48°	—	—	
2. Spilite augitite	Novaya Zemlya	44°	40°	—	
3. Ophitic Ab-c/pyrox. rock	Solomen, Karelia	—	40°	α1·685 γ1·708	Colourless
4. Ditto	Kendjarvi, Karelia	50°	39°	α1·697 γ1·720	Brown-violet ($Ca_{41}Mg_{37}Fe_{22}$ after Hess)
5. Albite diabase	Ballantrae	52°–54°	—	—	Colourless or purplish
6. Ophitic spilite	King I. Tasmania	51°	40°	Biref 0·030	Diopsidic

Sources: 1. Benson, 1915, p. 141; 2. Backlund, 1930, p. 32; 3 and 4 Eskola, 1925; 5. Balsillie, 1932, p. 125; 6. Scott, 1951a, p. 429.

The pyroxene of spilites has the same properties as the "normal pyroxene" of Scottish Permo-Carboniferous tholeiites (Walker, 1935, p. 140) which, as exemplified by an analysed sample of composition $Ca_{36}Mg_{45}Fe_{19}$ from Kinkell (Walker, Vincent and Mitchell, 1952, pp. 897–8) has

β 1·696 – 1·700 : mean 1·698
$2V\gamma$ 42° – 50° : mean 47°
Z : c 42° – 44° : mean 43°

The beautiful cervicorn habit adopted by the pyroxene in some of the spilites is a striking feature (Plate V, fig. 1). The crystals are slender, curving and branched, springing as tufts or plumes from a tangle of fine threadlike augite and feldspar, from the ends of a stouter short fascicle of augite rods, or from the tips of a prominent feldspar lath.

[1] A second pyroxene-like mineral reported by Bartrum (1936, p. 420) is actually babingtonite (Battey, 1954).

Their elongation may be very great—one crystal spanning the space between two adjacent centres of radiation was thirty times as long as it was wide (1·25 × 0·4 mm.). Sometimes a central rod may give off regular close-spaced branches at an angle of about 15° in frond-like fashion. Granules of iron-ore are strung along the augite rods, superficially embedded, and in many cases become elongated normal to the length of the rod extending far enough, at times, to lace adjacent augite branches together. Other examples of cervicorn or feathery pyroxenes in spilitic rocks come from Wales (Cox, 1915, p. 328) and Tasmania (Scott, 1951b, p. 115) and probably also from Timor (see footnote above).

Exactly similar cervicorn pyroxenes with associated iron ore are recorded from the variolites of Cruachan Dearg (Bailey *et al.*, 1924, figs. 51A and B, p. 305), quartz-dolerites of Talaidh type (*ibid.* p. 303) and tholeiites of Dalmahoy type (Campbell and Lunn, 1927). They are commonly found in pegmatitic segregations, acid veins and felsitic patches of tholeiitic flows and sills (Emerson, 1905; Falconer, 1908, p. 140; Bowen, 1910, pp. 660–1; Shannon, 1924, p. 16; Walker and Poldervaart, 1949, p. 643; Walker, 1952, pp. 394, 395–7). This type of crystallization has been linked by Walker (1952, pp. 397, 401) with conditions of free diffusion and these conditions would appear to be connected also with concentration of volatiles and alkaline residua in the rock.

This feature of pyroxene crystallization is important as indicating first that conditions of crystallization were comparable with those in some tholeiites and especially with their pegmatoid phases, and secondly that no crushing or metasomatic volume changes have since affected the rock, for such delicate structures as these would thereby be destroyed.

Another point about the pyroxene that must be strongly emphasized is its immunity from alteration. There are only the slightest occasional signs of uralitization or chloritization outside the area of thermal metamorphism. Although it is so frequently claimed throughout the literature that augite has altered to chlorite, in these New Zealand spilites, which contain abundant chlorite, there is, as Bartrum (1936, p. 421) has already reported, absolutely no evidence that it has been derived from the augite. Where the augite has been altered, by thermal metamorphism, the product is amphibole, not chlorite. The fact that the augite may be quite fresh has, of course, been used as an argument for primary precipitation of the associated albite from the beginnings of research into the spilites (Benson, 1915, pp. 141, 158–9) to the present day (Scott, 1951a, p. 430; Turner, 1948, p. 124).

Bright green, relatively highly birefringent, optically negative chlorite is an abundant constituent of the northern New Zealand spilites,

occurring in angular intersertal areas, in little rounded pools (Plate V, fig. 2), in fine veinlets running through the rock and in amygdales along with quartz. On the grounds of texture, including the lack of any pseudomorphous structure and its intersertal distribution in rocks whose other constituents are fresh and in which delicate structures in pyrogenetic minerals are undisturbed, as well as on grounds of its

TABLE 2.—CHLORITE FROM SPILITE

	I	II	III	Metal atoms to 18(O, OH) all Fe as Fe^{3+}		
SiO_2	27·88	27·51	27·11	2·987		4·00
TiO_2	—	—	0·35			
Al_2O_3	15·81	15·46	17·42	2·235	1·013	
Fe_2O_3	1·77	12·66	2·91		1·222	
FeO	31·92	17·56	30·98	3·046		5·89
MnO	0·51	0·05	n.d.			
MgO	9·52	13·46	9·75	1.595		
CaO	0·20	0·38	0·21	0·026		
Na_2O	—	0·08	n.d.			
K_2O	—	0·12	n.d.			
H_2O^+	11·97	11·87	11·07	8·039		8·04
H_2O^-	0·15	1·02	0·51			
Sum	99·88	100·38	100·31			
D	3·012	2·808	2·988			

	Orcel's parameters										
	s	f	a	α	β	γ	Biref.	2V	X	Y	Z
I	2·79	2·13	0·07	1·633	1·639	1·639	0·006	–ve			
II				Mean R.I. 1·628			0·005		yellowish-green	—	grass-green
III	2·34	2·47	0·10	1·638			0·010 (approx.)	–ve very small	pale yellow	grass-green	slightly darker green

I. Brunsvigite, Radauthal, Harz. Anal. J. Fromme (1902). No. 185, Table 31, Orcel, 1926, p. 382 (Optics, p. 416). II. Aphrosiderite, Ernsthausen, Lahn, between lava pillows. Anal. J. Holzner, 1938, p. 405. III. Chlorite (brunsvigite) intersertal in spilite (spec. 6210), Great Island, Three Kings Group, New Zealand. Anal. M.H. Battey.

composition, the chlorite is regarded as a primary mineral, representing the precipitate of a residual liquid greatly enriched in iron.

The chemical analysis and optical properties of a sample of chlorite separated from specimen 6210 are given in Table 2, with two similar chlorites from the literature for comparison. Mr. R. F. Youell of Leeds University very kindly carried out a preliminary X-ray examination of the mineral which confirmed its character as a true chlorite with a 14 Å basal spacing and further suggested that it might be an orthorhombic type.

In its mode of occurrence, and probably in its origin, the chlorite may be compared with the primary chlorophaeite described from the

tholeiites of the Dalmahoy type (Campbell and Lunn, 1927). Chlorophaeite is regarded by Peacock (1930, p. 177) as a "potential chlorite". This substance, and true chlorite, have sometimes been regarded as alteration products of the glassy mesostasis of tholeiites (Vincent, 1950, p. 49; Walker, Vincent and Mitchell, 1952, p. 901). In the cases quoted, however, the analyses of the glasses are given and it is clear that very large displacements of material would be required to convert either of them to such basic substances as chlorophaeite or chlorite. It is probably not in the minds of these writers that the necessary femic material came from outside the rock, but that the alteration of the glass took place at a late stage in the cooling history by the agency of the residual materials from the earlier crystallization. The distinction between patches of contiguous primary chlorophaeite and glass (Dalmahoy) and patches of glass partly altered to chlorite or chlorophaeite (Kap Daussy and Kinkell) then becomes quite narrow. In the spilites here described no evidence was seen of original intersertal glass. There is, however, strong evidence, to be detailed elsewhere, of the enrichment of originally glassy selvedges in iron and magnesium.

The prevailing iron-ore is titaniferous, as is shown by its incipient alteration to leucoxene in the amphibolized spilites. It is not known whether it is ilmenite or titanomagnetite, but its habit suggests the former. It occurs in close association with pyroxene in the variolitic types in the way already described, and elsewhere may occur as parallel sets of rods. Fine granular sphene (leucoxene) occurs in the groundmass of the rocks.

The norms of the analysed rocks show saturation with silica, and quartz is a regular though inconspicuous associate in most slices. It commonly appears as a little grain in each intersertal patch of chlorite (cf. quartz associated with chlorophaeite in the Dalmahoy rocks and opal with that in the Kinkell type) or in the interstitial potash feldspar. In some rocks it forms amygdales or narrow veinlets associated with chlorite, epidote, pumpellyite or babingtonite.

Apatite, present to about 1 per cent. in the norms of the analysed rocks, is rarely to be seen. It occurs conspicuously in two rocks where it is clearly of early crystallization.

In the associated keratophyres potash feldspar is found replacing albite in conspicuous fashion (Battey, 1955). In the spilites staining shows that it forms small interstitial areas of low birefringence and shadowy extinction and does no more than replace the tips of albite microlites. No effects were observed comparable with the advanced or complete replacement of plagioclase found in certain Derbyshire spilites (Sargent, 1917, pp. 13–16) in Roxburghshire (Tomkeieff, 1941) or in the poenites of Timor (de Roever, 1942, pp. 225–32).

No such importance is attained by the "secondary" minerals preh-

nite, epidote and calcite as is often described in connexion with spilites. They are on the contrary very sparingly present. In spite of the generally meagre development of epidote, however, two specimens are to hand, from Great Island, of epidosites composed entirely of epidote and quartz. Neither was in place. Bartrum mentions a concentration of epidote 8 inches thick and extending over several square feet, also from a fallen block. From the rarity and thorough-going alteration of these types it may be suspected that they are of the same character as those described by Eskola (1925) which are strictly local, starting at fissures and extending a short distance each side with sharp borders against unaltered greenstones. Carbonate was observed only as cavernous patches a few centimetres across at the base of pillow lavas in one exposure and microscopically in slides from the basal part of another flow. Bartrum records calcite veins from the type area for pillow spilite on Great Island. This spot was inaccessible at the time of the writer's visit but the analysed rock from there has been examined and appears perfectly fresh, though traversed by a small vein of prehnite with a little babingtonite.

Babingtonite also occurs in fine veinlets with quartz traversing the unaltered spilite, and as isolated crystals of late precipitation in areas of interstertal chlorite. Its properties are:

α	$1{\cdot}713 \pm 0{\cdot}003$	X	bright green
β	$1{\cdot}724 \pm 0{\cdot}003$	Y	pale purple brown
γ	$1{\cdot}744 \pm 0{\cdot}005$	Z	strong purple brown
$2V\gamma$	80°, 85°, 86°		

Dispersion $r > v$ distinct.

Extinction angle Z: cleavage (001) in sections normal to Y = 47°.

One good cleavage is shown in sections normal to Y.

Pumpellyite, occasionally found in vesicles has the following properties:

		X	almost colourless
β	1·715	Y	bluish-green
γ	1·722	Z	almost colourless
$2V\alpha$	86°, but variable		
Z : c	24°–30°		

These properties indicate a somewhat higher iron content than any material analysed by Coombs (1953) in his study of the pumpellyite series. The data conform fairly closely with his curves though the optic axial angle has a somewhat smaller negative value than might be expected from the β index.

Thermal metamorphism has affected the spilites on the northern shore of Doubtless Bay. The principal results have been amphiboliza-

TABLE 3.—CHEMICAL ANALYSES OF SPILITES

	AUC 559	5314	6210	D	5318	5310	A (cf.6228)
SiO_2	52·94	53·59	54·87	55·86	56·13	57·66	63·58
TiO_2	2·54	2·76	2·02	1·60	2·21	1·94	0·99
Al_2O_3	12·81	14·22	14·98	15·17	14·71	15·90	13·42
Fe_2O_3	3·76	2·03	1·65	2·54	1·39	1·71	2·10
FeO	9·29	9·66	8·89	6·98	9·05	6·80	5·67
MnO	0·21	0·05	0·04	0·19	0·16	0·01	0·14
MgO	3·65	3·58	3·33	2·30	4·87	3·07	1·37
CaO	6·22	6·18	4·06	3·39	2·24	2·55	2·75
Na_2O	5·25	5·52	5·73	5·45	4·58	5·06	4·31
K_2O	0·18	0·41	1·13	2·05	2·80	2·81	2·93
H_2O^+	2·33	1·49	2·39	2·53	1·66	1·44	1·85
H_2O^-	0·21	0·39	0·25	1·21		0·21	0·30
P_2O_5	0·36	0·34	0·47	0·63	0·38	0·47	0·35
CO_2	–	–	–	tr.	–	–	0·03
Rest	0·16	–	–	0·20	–	–	0·10
Total	99·91	100·22	99·81	100·07	100·18	99·63	99·89
D	2·90	2·88	2·82		2·82	2·79	2·77

NORMS

qu	3·18	0·54	1·02	3·42	2·46	5·22	17·65	
or	1·11	2·22	6·67	12·23	16·68	16·68	17·31	
ab	44·54	46·63	48·21	46·63	38·77	42·97	36·44	
an	10·56	12·79	11·95	10·56	8·06	9·17	8·65	
cor	–	–	–	–	1·12	1·12	–	
di $CaSiO_3$	7·31	6·73	1·97	1·16	–	–	2·27	
di $MgSiO_3$	3·40	2·90	0·80	0·50	–	–		
di $FeSiO_3$	3·83	3·83	1·19	0·66	–	–		
hy $MgSiO_3$	5·70	6·00	7·50	5·30	12·20	7·79	9·56	
hy $FeSiO_3$	6·34	7·66	10·43	7·79	12·01	7·70		
mt	5·57	3·02	2·55	3·71	2·09	2·55	3·06	
ilm	4·71	5·32	3·80	3·04	4·26	3·65	1·88	
ap	1·01	0·67	1·34	1·34	1·01	1·34	0·84	

REFERENCE

AUC 559 . Pillow-spilite, base of north-west cliff, Great Island. (Bartrum, 1936.)

5314 . . Amphibolized spilite, S.E. of entrance to Brodie's Creek, Rangiawhia Peninsula.

6210 . . Spilite cascade,, upper Tasman Stream, Great Island. (cf. Chlorite analysis, Table 2.)

D . . "Andesite" Mt. Camel. (Bartrum, 1929.)

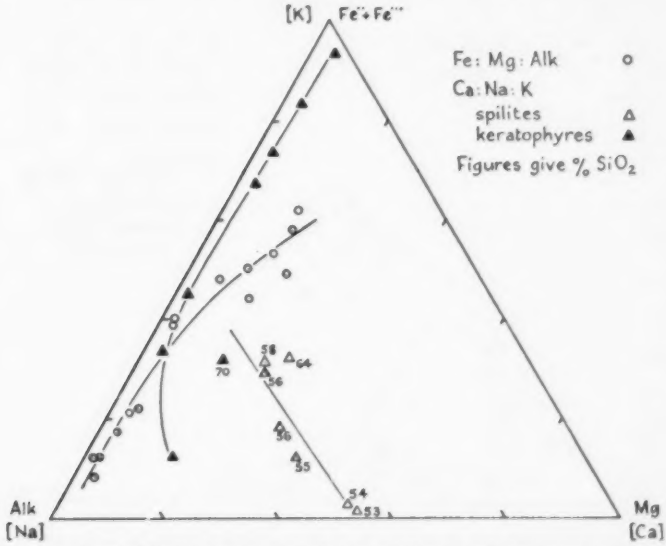
5318 . . Amphibolized spilite with biotite, S.E. of entrance to Brodie's Creek, Rangiawhia Peninsula.

5310 . . Contact altered spilite with biotite, E. shore of Brodie's Creek, Rangiawhia Peninsula.

A. (cf. 6228) . Semi-basic spilite, blocks at North West landing-place Great Island ("Albitic porphyry" Bartrum, 1936).

Analyses AUC 559, A and D by F. T. Seelye. Others by M. H. Battey.

tion of the pyroxene and chlorite and the development of a calcic plagioclase (An_{30-48}) in place of albite. In a general way these changes are the same as those recorded by Flett (1913) in albite diabases and spilites from the aureole of the Dartmoor granite. Flett suggested that the lime released in amphibolization forms anorthite in the plagioclase. In the present case also the process is roughly isochemical, for analyses show (Table 3) that the amphibolized spilites are little changed in composition by the metamorphism. Eskola (1925, p. 21) found similarly that amphibolization by regional metamorphism scarcely affected



TEXT-FIG. 1.—Differentiation trends in spilites and keratophyres from northern New Zealand. Figures give silica percentages of spilites in Ca: Na: K field.

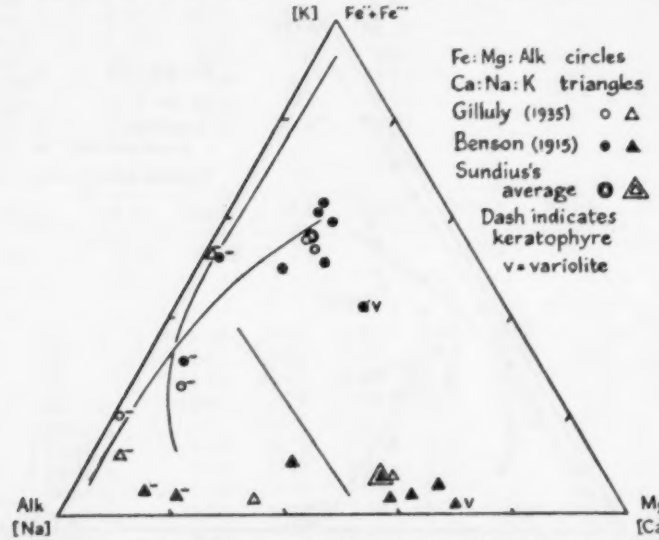
the bulk composition of original albite-clinopyroxene rocks. Attention will be confined, here, to the petrography of the unmetamorphosed rocks, but the analyses of the amphibolized types are included in Table 3 and plotted on the diagrams.

CHEMISTRY OF THE SPILITIC SERIES

Table 3 presents seven analyses of spilites from northern New Zealand, four of which are new analyses. These, together with eight analyses of the associated keratophyres already published (Battey, 1955) are plotted in Text-fig. 1 to exhibit the course of variation of their major elements. The trend of variation in the atomic proportions of Fe : Mg : Alk is simple and may be satisfactorily represented by

a smooth curve. The two rocks that fall off the main course of differentiation in the direction of Mg come from the zone of weak thermal metamorphism and may possibly have suffered some small change in composition, but probably the displacement is due to normal variability.

In the proportions of Ca : Na : K a trend may be seen amongst the spilites running with increasing acidity (shown by the silica percentage written alongside each point) from AUC559 to 6249. The latter is an example of a transitional rock carrying a small amount of pyroxene but falling in the silica range of the keratophyres. This trend takes the



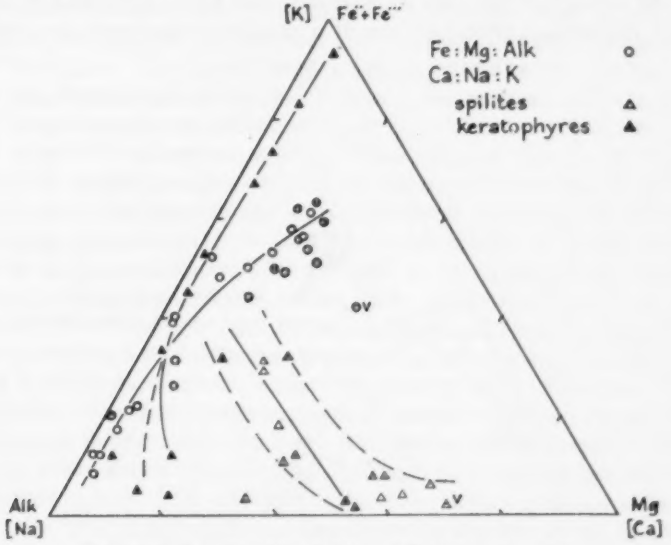
TEXT-FIG. 2.—Analyses of spilites and keratophyres from New South Wales and Oregon. Curves are those of Text-fig. 1.

form of a narrow zone with a roughly constant proportion of sodium and steadily diminishing calcium and increasing potassium directed towards a "prototype keratophyre" with roughly equal proportions of sodium and potassium. Such a rock would in this respect correspond with an unaltered rhyolite. It has already been shown, however, that in common with other keratophyres (and old rhyolites in general) the more acid members of our series have widely variable alkali ratios as a result of the later migration of these constituents (Battey, 1955). This is expressed by a second Ca : Na : K trend, restricted entirely to acid members of the group, which runs along the sodium-potassium side of the triangle. The rocks whose compositions lie along this line are believed to have diverged from an original condition of equality of alkalis towards which the spilite evolutionary trend is directed.

In Text-fig. 2 analyses of the spilitic rocks published by Benson

(1915) and Gilluly (1935) together with Sundius's (1930) average spilite are plotted in the same way, for comparison with the New Zealand rocks, and in Text-fig. 3 are shown all the points of Text-figs. 1 and 2. The curves controlled by the New Zealand rocks alone are shown on this diagram along with the modifications suggested by the additional points of Text-fig. 2.

The points marked "V" in Text-figs. 2 and 3 represent the analysis of a variolite given by Benson (1915) and its anomalous position raises a general point about published analyses of spilites. In the present

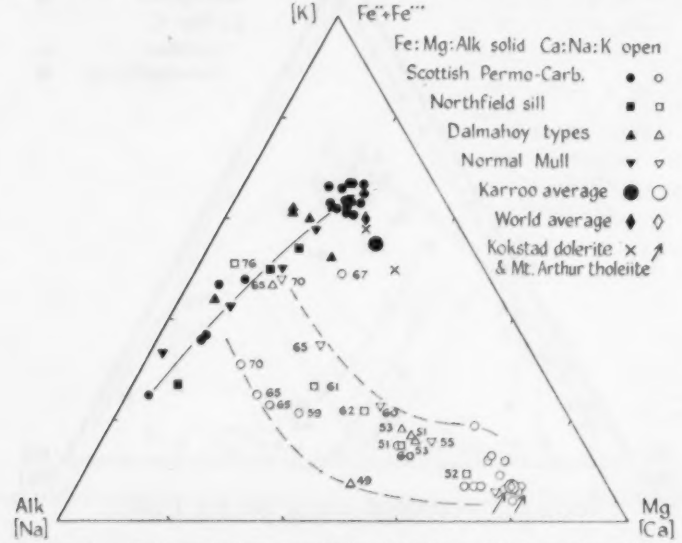


TEXT-FIG. 3.—Combined data of Text-figs. 1 and 2.

study it was found that the dark perlitic devitrified selvedges of the pillow lavas do not always represent the composition of a former liquid, as chilled phases are often supposed to do, but on the contrary sometimes possess an aberrant basic and iron-rich composition which, in the cases studied, is approximately that of biotite. Other workers have found compositions high in iron, magnesia or lime. Variolitic phases of spilites commonly occur towards the outsides of pillows and contain between the varioles a high proportion of material similar to the selvedge. Analyses of these types, therefore, ought not to be accepted as representing points on the spilitic liquid line of descent without careful scrutiny. It seems likely that the very basic nature of the analysed spilites from Devonport Workhouse Quarry (Flett, 1907, p. 97) with 40·55 per cent. SiO_2, Chipley (Flett, 1913, p. 56) with 39·28 per cent. SiO_2, and Almwch, Anglesey (Greenly, 1919, p. 55) with 39·20

per cent. SiO_2, is to be explained by the inclusion of some selvedge material in the analytical samples. The Devonport rock is said (*loc. cit.* p. 96) to represent an unusual type in that it carries large phenocrysts of feldspar (also noted in selvedges from New Zealand). The groundmass is of acicular feldspars in a matrix of chlorite and devitrified glass. If these particular analyses are of a mixture of pillow lava and selvedge this circumstance explains also the relative basicity of Wells's (1923) average spilite, in which these analyses exercised a marked influence, compared with that of Sundius (1930).

As a result of the work of Nockolds and Allen (1953) and Walker and Poldervaart (1949) we are in a position to compare the trends



TEXT-FIG. 4.—Differentiation trends in tholeiites. Figures give silica percentages in Ca : Na : K field. Authorities cited in text.

shown by the spilitic series with those of a large number of examples of differentiation in calc-alkaline and tholeiitic magmas. From this comparison it is clear that in regard to the proportions of Fe : Mg : Alk the spilitic series is virtually identical with the subdivision of the tholeiite series represented by late Palaeozoic quartz-dolerites and tholeiites of Scotland and the north of England. In Text-fig. 4 the analyses of these rocks and their segregations are plotted, with the average Karroo dolerite (Walker and Poldervaart, 1949) and an average world tholeiite based on 137 analyses (Nockolds, 1954). Comparing this with Text-fig. 3 the main field of basic spilites is seen to be contiguous with that of tholeiites on the Fe : Mg : Alk curve, but lies a little along the curve of variation on the Fe-Mg-poor side

of the tholeiite field. On the Ca : Na : K curve the fields of tholeiites and basic spilites are again contiguous and there is some overlap of the spilite field by the tholeiites of Dalmahoy type which link the tholeiites with their segregation products. An early deficiency of potash is shown in spilites as compared with tholeiites with the same ratio of alkalis to lime. This deficiency, which amounts usually to some tenths of one per cent. only, was noted by Sundius (1930) and Gilluly (1935) and seems to be a constant feature. More acid members of the series (around 55 per cent. SiO_2) show no relative shortage of potash, however, and a little interstitial potash feldspar occurs in them so that there is apparently no ineluctable lack of this constituent in the magma. Presumably the low potash of basic spilites is due to the fact that potash fails to find a place in the minerals stable under the conditions of consolidation of spilites until iron and magnesium are somewhat reduced in amount. There certainly appears to be a range of conditions under which chlorite is stable, rather than biotite, in the presence of potash, and where the potash possesses a migratory tendency (at any rate over short distances) instead of precipitating locally as potash feldspar (Chayes, 1955, p. 79). There is some suggestion that potash becomes locked up in glassy phases of the lava, for devitrified selvedges from Doubtless Bay that have been thermally metamorphosed are composed largely of very fine crystalline biotite and an analysed specimen carries 7·54 per cent. K_2O. The proximity of the later intrusion, however, makes it uncertain whether the potash in them is indigenous to the lava. But another case is known to the writer where biotite forms an important part of a selvedge to a pillow which is remote from any intrusion, while Fenner (1931) quotes a selvedge high in potash from a lava pillow in the Watchung basalts. Some explanation of the whereabouts of the potash may lie in this direction, though other published analyses of selvedges show a chloritic composition low in alkalis, and at present information on the potash question is inconclusive. Local concentrations are clearly possible (Sargent, 1917; Tomkeieff, 1941; de Roever, 1942).

It may be concluded from the study of the analyses that the spilitic series is the product of a modification of the normal trend of tholeiitic magmas. From the petrography it is concluded that the low temperature mineralogy of the spilites is also no more than an intensification of processes already seen in some types of tholeiite.

Petrogenesis

The problem of the spilites becomes, therefore, that of explaining the low temperature mineralogy of the rocks and the deviation shown in the trend of the Ca : Na : K curve along the early part of its length from that of the otherwise closely comparable tholeiites.

The magma of the spilites was apparently almost wholly liquid at the time of its emplacement, for phenocrysts are rare. In discussing later events attention may be confined to a single small discrete mass of this liquid, as for example a single lava pillow, for where the lavas are pillowy each separate mass seems to have followed the same course of crystallization. No abstraction of solid phases has been possible and the integrity of the enclosing selvedge restricts to some degree the possible postulates of flowing solutions traversing the main body of the pillow.

Recent experimental work on phase relations among silicates under pressure of water vapour has emphasized not only the predicted lowering of melting points but also the importance of water itself as a component (Yoder, 1952). The presence of water and its amount may radically change the mineral assemblage crystallizing from a mixture of a given water-free composition. In particular, chlorite is now found to be stable in the presence of excess water at higher temperatures (680°C.) than had been expected (Yoder, 1952, p. 619). Low albite, the other conspicuous low temperature mineral present in the spilites is believed to be the stable phase below about 700°C. (Tuttle and Bowen, 1950). These results bring the stability range of chlorite close to the temperature at which the system quartz-albite-orthoclase water (at high pressures) is wholly liquid, this temperature being below that of the inversion of high to low albite. Thus, as far as our information goes, there is apparent agreement between the petrographic data on the course of the later stages in spilitic crystallization and the experimentally determined stabilities of the phases. While the system to which this information directly applies is some distance from the assumed composition of the residual spilitic liquid, the difficulties of accepting the precipitation of albite and chlorite as successive stages in magmatic crystallization under hydrous conditions are nevertheless greatly reduced.

One of the principal objections to the primary character of the spilite assemblage has been the association of augite and albite. In seeking to explain this we have to rely upon petrographic evidence. It seems likely, from such evidence, that the fresh augite has persisted metastably, and may have in part precipitated metastably from a liquid in which high water content and consequent free diffusion has permitted the plagioclase to pass down the curve of continuous reaction to produce albite. It is clear from the presence of pyroxene in the late veins of dolerites that this mineral can continue to crystallize under high volatile and low temperature conditions. The descriptions by Shannon (1924, pp. 22–27) of the albite-diopside pegmatites in the Goose Creek diabase (tholeiitic magma type) are of great interest in this connexion. He describes the mantling or replacement of purplish

titaniferous augite by diopside, with a change in the associated plagioclase from labradorite to albite, around the margins of pegmatite veins, while in their centres diopside, considered probably of primary precipitation, is in intergrowth with albite. The mantling of augite by diopside reverses the usual trend of change in pyroxene composition in basaltic lavas, and may be compared with abnormal zoning in pyroxene from a dolerite of Mount Arthur, East Griqualand (Walker and Poldervaart, 1949, p. 643). The plumose texture of the Goose Creek pegmatitic pyroxene is a feature reproduced in late doleritic veins or patches generally, and in the spilites.

It has been stated (Kennedy, 1931, 1933) that the characteristic pyroxene of tholeiites is pigeonite; but, while this mineral is described from South African and Tasmanian occurrences, it is not the normal pyroxene of the Scottish and North of England late Palaeozoic suite, (Walker, 1935; Walker, Vincent and Mitchell, 1952; Campbell and Lunn, 1927) nor is it recorded from many of the Tertiary tholeiites of Mull (*Mull Memoir*, pp. 16–18, 145–6, 147–50, 284–5, 370–3). There is thus some indication that with enrichment in volatiles and lower temperatures a more lime-rich pyroxene can be precipitated from tholeiitic liquids. The introduction of small Fe^{2+} ions in place of Ca^{2+} distorts the pyroxene structure (Edwards, 1942, p. 598) so that the introduction of calcium is a more likely process at low temperatures.

With these points in mind the following scheme may be suggested for the spilite paragenesis. Under highly hydrous conditions a single pyroxene relatively rich in lime was rapidly crystallized, probably in part metastably, along with plagioclase which, under the prevailing conditions of free diffusion, was continuously reacted upon with the elimination of anorthite. Some of the calcium so released may have been taken up by the pyroxene. As the result of the failure of pigeonite to form, a large amount of iron accumulated in the residual liquid and was precipitated as iron-rich chlorite together with a little quartz, as a final product. In the more acid spilites the latest liquid to crystallize precipitated also some poorly crystalline interstitial potash feldspar. Concentration of iron and calcium in the late crystallizing residues is shown by the presence of babingtonite with quartz in a few cases and the fact that the pumpellyite is an iron-rich variety. Some calcium and iron have been transported wholly from the rock to form occasional veins of prehnite and small masses of epidosite and calcite; but in the rocks studied there is no evidence of any large scale migration of material.

It may be questioned whether either the postulate of a specially soda-rich primary magma, or that of introduction of soda from some outside source is necessary to explain the composition of spilites. In the consolidation of a basaltic magma, subaerially or in dry sediments,

a considerable loss of water vapour and other volatile constituents must occur. The very significant effects so produced, by a magma thought to have normal volatile content, are described by Walker and Poldervaart (1949) in connexion with the Karroo dolerites, where notable bodies of granophyric and other igneous-looking rocks have been formed by transfusion of sediments. These authors remark on the paucity, in the dolerite, of pegmatitic schlieren and other evidence of the retention of late volatiles, such as is shown by the Scottish Permo-Carboniferous tholeiites. Another example of the effects of escaping volatiles is that of the Gowganda Lake sills (Bowen, 1910). It is often difficult to determine the nature of these emanations but it seems clear that alkalis and iron have formed an important part of them and have moved in fluid solutions.

If it can be postulated that one of the effects of a high external pressure of water vapour is to cause the retention of volatiles in the igneous rock, preventing the loss of alkalis and iron, then its composition would be modified in the direction of spilite. Although petrographic evidence suggests that this may be the case, it is not quite clear why it should be so. In experimental silicate studies under pressure of water vapour careful jacketing of the charge with material of the same composition is necessary to prevent transport of the reacting substances; but in a lava flow this function of the "buffer" may be discharged by a relatively thin layer of the rock at the upper and lower surfaces—in the case of a lava pillow even by the selvedge, in which composition changes definitely have occurred. In any case, it does appear that doleritic rocks like those of Tasmania and South Africa show much less sign of high internal water content and concentration of other volatile oxides, than, say, the Scottish tholeiites and dolerites, as expressed in the amount of acid residuum, the alkali content, the textures of crystallization and the amount of hydrous silcates present. Von Eckermann (1938) has also drawn attention to the marked differences with respect to their sodic differentiates that distinguish otherwise similar basic eruptives.

Strong evidence that some of the changes mentioned in crystallization trend are, in fact, due to enrichment in water is given by Poldervaart's (1946) description of the conversion of olivine dolerite to tholeiite by the addition of water distilled from sedimentary inclusions. Points representing the dolerite and tholeiite are plotted on Text-fig. 4 to show the direction of change in composition which is the same as that from Karroo dolerite to Scottish tholeiite.

If the spilitic mineralogy is dependent primarily upon the effect of a hydrous environment, and hence the water content of the magma, in lowering the temperature of completion of crystallization, modifying the phases precipitating and retaining the volatile solutions, it is to be

expected that a tholeiitic magma may approach a spilitic condition in varying degree, depending upon the wateriness of its environment. In short, a series will exist from "dry tholeiite" to "wet tholeiite" to spilite. Edwards (1942, p. 465 and Table 3) has pointed out that a gradation exists from dolerites of Tasmanian type through the Karroo type to that of Scotland and the North of England. This change, he observes, involves (1) increase in Na_2O and decrease in CaO and Al_2O_3; (2) increase in iron; (3) increase in TiO_2; (4) increase in P_2O_5. To these trends we may add (5) decrease in MgO; (6) higher state of oxidation of iron; (7) increase in combined water.

In Table 5 it is shown that this sequence may be extended through the range of tholeiites to what might be termed the "subspilitic" tholeiites of Dalmahoy type and to the spilites proper. The whole of

TABLE 4.—CHEMICAL ANALYSES OF TABLE 3 CALCULATED WATER-FREE AND TO 100

	AUC 559	5314	6210	D	5318	5310	A (cf. 6228)
SiO_2	54·4	54·5	56·5	58·0	57·0	58·8	65·2
TiO_2	2·6	2·8	2·1	1·7	2·2	2·0	1·0
Al_2O_3	13·2	14·5	15·4	15·8	15·0	16·2	13·8
Fe_2O_3	3·9	2·1	1·7	2·6	1·4	1·7	2·2
FeO	9·5	9·8	9·1	7·2	9·2	6·9	5·8
MnO	0·2	0·1	0·0	0·2	0·2	0·0	0·1
MgO	3·7	3·6	3·4	2·4	4·9	3·1	1·4
CaO	6·4	6·3	4·2	3·5	2·3	2·6	2·8
Na_2O	5·4	5·6	5·9	5·7	4·6	5·2	4·4
K_2O	0·2	0·4	1·2	2·1	2·8	2·9	3·0
P_2O_5	0·4	0·3	0·5	0·6	0·4	0·5	0·3
Others	0·1	–	–	0·2	–	–	–

this sequence is not generally found in the rocks of any one locality. The rocks of a particular province cover only a small part of the range, their position being determined by the environment. The existence of this gradation is regarded as evidence against the concept of a special spilitic magma, distinct from other primary magmas, as proposed by Dewey and Flett (1911), and also as opposing the view advanced by Gilluly (1935, p. 348) that the spilites represent "normal" basalt magma mixed with, or lavas metasomatised by, emanations from subjacent trondhjemitic magma. It is not, of course, intended to deny that there has been any movement or concentration of particular constituents by fluid transport after the consolidation of the rock; but the regional modification of large rock volumes by external solutions is not upheld by the study of either spilites or keratophyres from northern New Zealand.

The view here taken of the relationship of spilites to tholeiites has already been foreshadowed in one of the last papers of the late Professor Paul Niggli (1952). He shows, by the use of his own system of

TABLE 5.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
SiO_2	52·65	51·78	51·82	53·03	52·04	49·10	50·54	51·53	50·27	52·90	48·52	51·19	51·22	52·94
TiO_2	0·58	0·92	1·34	1·38	1·06	4·02	2·80	1·57	2·63	2·35	1·73	2·69	3·32	2·54
Al_2O_3	16·23	15·34	14·76	13·92	14·26	12·13	12·86	11·05	13·07	13·02	13·07	14·40	13·66	12·81
Fe_2O_3	0·51	1·07	1·22	2·21	2·77	4·61	4·13	2·73	4·28	6·62	5·22	4·43	2·84	3·76
FeO	8·21	10·58	9·24	10·24	9·27	8·92	8·75	10·98	9·66	6·31	7·85	9·04	9·20	9·29
MnO	0·15	0·22	0·12	0·36	0·33	0·15	0·32	0·45	0·14	—	0·49	0·21	0·25	0·21
MgO	6·64	6·44	7·32	4·62	6·12	4·50	4·63	5·21	4·42	2·86	7·21	4·51	4·55	3·65
CaO	11·34	9·88	10·02	9·36	9·04	8·20	8·74	9·68	8·23	6·37	5·89	6·05	6·89	6·22
Na_2O	1·58	2·54	2·06	2·55	3·13	2·14	2·89	3·48	3·44	3·51	5·29	4·18	4·93	5·25
K_2O	0·90	0·66	0·82	0·92	0·91	2·10	1·43	0·86	0·98	2·00	0·74	0·78	0·75	0·18
H_2O^+	0·48	0·63	0·84	1·19	1·04	2·50	2·25	1·26	1·39	3·73	2·99	1·82	1·88	2·33
H_2O^-	0·85	Nil	0·14	0·32	0·18	1·02	0·17	0·71	0·10		1·48	0·24		0·21
P_2O_5	0·01	0·14	0·12	0·08	tr.	0·51	0·34	0·22	0·69	0·90	0·30	0·40	0·29	0·36
etc.						0·03	0·39	0·34	0·91	—	0·07	0·19	0·94	0·16
Sum	100·13	100·20	99·82	100·18	100·15	99·93	100·24	100·07	100·21	100·57	100·85	100·13	100·72	99·91

A. Average undifferentiated Tasmanian dolerite (6 analyses) (Edwards, 1942, p. 465, Table 3, No. 1).
B. Karroo dolerite, Alewyn's Gat, Bulthouder's Bank sill. (Walker and Poldervaart, 1949, Table 15, No. 5.)
C. Lower chilled phase of Palisade diabase 1 ft. above base (Walker, 1940, Table 3, col. 1).
D. Marginal tholeiite, Karroo suite, Farm Linton, Mt. Arthur, East Griqualand. (Walker and Poldervaart, 1949, Table 15, No. 52.)
E. Tholeiite associated with sedimentary inclusion, Mt. Arthur, E. Griqualand (*Ibid.* Table 15, No. 72).
F. Tholeiite, Kinkell Quarry, Kirkintilloch, Dumbartonshire. (Walker, 1935, Table III, No. 11.)
G. Basalt, compact Central type, Monadh Beag, Mull. (Mull Memoir, Table II, p. 17, No. IV.)
H. Tholeiite, Brunton type, 5½ m. S.E. of Tobermory, Mull. (*Ibid.*, Table II, p. 17, No. VI.)
I. Quartz-dolerite dyke, Skaergaard Pena. E. Greenland. (Vincent, 1953, Table III, No. III.)
J. Tholeiite, Dalmahoy type, Ravelrig Quarry, Dalmahoy, Scotland. (Campbell and Lunn, 1927, p. 501.)
K. Dolerite, Dalmahoy type, Auchinoon, Dalmahoy, Scotland. (Campbell and Lunn, 1927, p. 501.)
L. Quartz-dolerite, Munro's Creek, Nundle, New South Wales. (Benson, 1915, p. 139, No. 1021.)
M. Average spilite. (Sundius, 1930, p. 9.)
N. Spilite, Great Island Three Kings Group. (Bartrum, 1936, p. 417.)

handling chemical data, that in the central zone of the Greenstone flow of the Michigan Keweenawan a magma rich in volatiles assumed the character of a spilitic residual magma. He concludes that the replacement of water-free by hydrous silicates took place at an early stage (p. 404) and regards the Greenstone rocks as a suitable starting point for study of the early stages of the development of spilitic lavas. He appears to have believed that separation of the residuum of crystallization from a body of different form would produce this lava.

> "In the central part of the thick Greenstone flow the differentiation could only develop internally and without complete separation" (p. 406).

In this respect his line of thought was somewhat different from that here followed.

Vincent (1953) discusses the derivation of lamprophyric dyke-rocks in East Greenland from normal basaltic magma by a process of fractional crystallization accompanied by an increase in the water content of the residual liquid, both the alkalis and the aqueous fluids being regarded as present in the original magma. The normal dolerites of East Greenland he compares with Normal Mull types. They precipitate a diopsidic augite (comparable with that of the Scottish Permo-Carboniferous tholeiites and the spilites) neither orthopyroxene nor pigeonite being present (p. 27). Intermediate between normal dolerite and lamprophyre are alkaline dolerites, and Vincent remarks (p. 31) upon the resemblance of these to spilites. He suggests that the magmatic processes giving rise to the oligoclase dolerites, which form 23 per cent. of the injected rock at the level of exposure, may well be similar to those responsible for spilites. The present writer would be inclined to lay greater emphasis on the similarity of the analysed sodic quartz-dolerite (50·27 per cent SiO_2) to the leading type of spilite. The oligoclase dolerite in its greater basicity (45·76 per cent. SiO_2, more basic indeed than its assumed parent) suggests that here some mechanism of separation into femic and salic portions such as Vincent infers (p. 44) in lamprophyre development may already have begun.

These two sets of observations serve to strengthen the view that the spilites are genetically connected with tholeiites, and that conditions of crystallization and retention of volatiles explain their mineralogy and composition, rather than a peculiarity of the initial magma, or later introduction of soda and emigration of other constituents.

Study of the North Auckland spilites reaffirms the original view of Dewey and Flett that the series from spilite to keratophyre is a true differentiation series, suggests that its special mineralogy is primarily due to the influence of water as a component of the magma, and serves to connect the series with the several subdivisions that may be made of the broader Tholeiitic Series.

The recognition of the Spilitic Series remains, of course, of great value as an index of environment of crystallization, and observation of the degree to which spilitic mineralogy is approached in a tholeiitic magma may extend its usefulness still further.

ACKNOWLEDGMENTS

The field work on which this study is based was assisted by a grant from the Hutton Memorial Fund of the Royal Society of New Zealand. Laboratory study was carried out, during the tenure of a British Council Research Scholarship, in the Department of Mineralogy and Petrology, Cambridge, under the direction of Professor C. E. Tilley, for whose advice and encouragement the writer is most grateful. He extends his thanks also to other members of the staff of the Department for advice and help in many aspects of the work. Dr. S. R. Nockolds has most kindly undertaken the task of seeing the paper through the press in the writer's absence from England.

Postscript :—For a full analysis of differentiation in tholeiitic series, and subdivision of the range of variation shown in the present text-fig. 4, see Nockolds, S. R., and R. Allen, 1956. The geochemistry of some igneous rock series—III. *Geochimica et Cosmochimica Acta*, ix, 34–77.

REFERENCES

BACKLUND, H. G., 1930. Die Magmagesteine der Geosynklinale von Nowaja Semlja. *Rept. of scientific results of Norwegian Exped. to Novaya Zemlya, 1921*, No. 45. Oslo.

BAILEY, E. B., *et al.*, 1924. The Tertiary and the post-Tertiary geology of Mull, Loch Aline and Oban. *Mem. Geol. Surv. Scot.*

BALSILLIE, D., 1932. The Ballantrae igneous complex, S. Ayrshire. *Geol. Mag.*, lxix, 107–130.

BARTRUM, J. A., 1929. Igneous rocks at Mount Camel, Hohoura, North Auckland. *N.Z. Journ. Sci. & Techn.*, x, 356–360.

—— 1936. Spilitic rocks in New Zealand. *Geol. Mag.*, lxxiii, 414–423.

BATTEY, M. H., 1950. The geology of Rangiawhia Peninsula, Doubtless Bay, North Auckland. *Rec. Auck. Inst. & Mus.*, iv, (1), 35–59.

—— 1951. Notes to accompany a topographical and provisional geological map of Great Island, Three Kings Group. *Rec. Auck. Inst. & Mus.*, iv. (2) 93–8.

—— 1954. The occurrence of babingtonite in spilite from Three Kings Islands. *Rec. Auck. Inst. & Mus.*, iv (5), 263–6.

—— 1955. The petrology of some keratophyres from New Zealand. *Geol. Mag.*, xcii, 104–126.

BENSON, W. N., 1915. The geology and petrology of the Great Serpentine Belt of New South Wales. Part iv. The dolerites, spilites and keratophyres of the Nundle district. *Proc. Linn. Soc. N.S.W.*, xl, 121–173.

BOWEN, N. L., 1910. Diabase and granophyre of the Gowganda Lake district, Ontario. *Journ. Geol.*, xviii, 658–674.

CAMPBELL, R., and J. W. LUNN, 1927. The tholeiites and dolerites of the Dalmahoy syncline. *Trans. Roy. Soc. Edinb.*, lv, 495–504.

CHAYES, F., 1955. Potash feldspar as a by-product of the biotite-chlorite transformation. *Journ. Geol.*, lxiii, 75–82.

COOMBS, D. S., 1953. The pumpellyite mineral series. *Miner. Mag.*, xxx, 113–135.

COX, A. H., 1915. The Geology of the District between Abereiddy and Abercastle (Pembrokeshire). *Quart. Journ. Geol. Soc.*, lxxi, 273–342.

DEWEY, H., and J. S. FLETT, 1911. Some British pillow-lavas and the rocks associated with them. *Geol. Mag.*, (Dec. 5), viii, 202–209, 241–248.

ECKERMANN, H. VON., 1938. A contribution to the knowledge of the late sodic differentiates of basic eruptives. *Journ. Geol.*, xlvi, 412–437.

EDWARDS, A. B., 1942. Differentiation of the dolerites of Tasmania. *Journ. Geol.*, l, 451–480, 579–610.

EMERSON, B. K., 1905. Plumose diabase and palagonite from the Holyoke trap sheet. *Bull. Geol. Soc. Amer.*, xvi, 91–130.

ESKOLA, PENTTI, 1925. On the petrology of Eastern Fennoscandia, I. The mineral development of basic rocks in the Karelian formations. *Fennia*, xlv, 1–93.

FALCONER, J. D., 1908. Igneous geology of the Bathgate and Linlithgow Hills, Pt. II. *Trans. Roy. Soc. Edinb.*, xlv, 133–150.

FENNER, C. N., 1931. The residual liquids of crystallizing magmas. *Miner. Mag.*, xxii, 539–560.

FLETT, J. S., 1907. *in* The geology of the country around Plymouth and Liskeard. *Mem. Geol. Surv. Gt. Brit.*

—— 1913. *in* Geology of the country around Newton Abbott. *Mem. Geol. Surv. Gt. Brit.*

FROMME, J., 1902. Brunsvigit, eine neues Leptochlorit aus dem Radauthale. *Min. Pet. Mitt.*, xxi, 171–7.

GILLULY, J., 1935. Keratophyres of eastern Oregon and the spilite problem. *Amer. Journ. Sci.* (5), xxix, 225–252; 336–352.

GREENLY, E., 1919. Geology of Anglesey, Vol. I. *Mem. Geol. Surv. Gt. Brit.*

HESS, H. H., 1949. Chemical composition and optical properties of common clinopyroxenes. *Amer. Mineral.*, xxxiv, 621–666.

HOLZNER, J., 1938. Eisenchlorit aus dem Lahngebiet: chemische Formel und Valenzausgleich bei den Eisenchloriten. *Neues Jb. Min.*, B.B. lxxiii, Abt. A., 389–417.

KENNEDY, W. Q., 1931. The parent magma of the British Tertiary Province. *Geol. Surv. Summ. Progr. for 1930*, Pt. II, 61–73.

—— 1933. Trends of differentiation in basaltic magmas. *Amer. Journ. Sci.*, xxv, 239–256.

NIGGLI, P., 1952. The chemistry of the Keweenawan lavas. *Amer. Journ. Sci., Bowen Volume*, 381–412.

NOCKOLDS, S. R., 1954. Average Chemical Composition of some Igneous Rocks. *Bull. Geol. Soc. Amer.*, lxv, 1021.

—— and R. ALLEN, 1953. The geochemistry of some igneous rock series. *Geochimica et Cosmochimica Acta*, iv, 105–142.

ORCEL, M. J., 1927. Recherches sur la composition chimique des chlorites. *Bull. soc. franç. min.*, l, 75–456.

PEACOCK, M. A., 1930. The distinction between chlorophaeite and palagonite. *Geol. Mag.*, lxvii, 170–178.

POLDERVAART, A., 1946. The petrology of the Mount Arthur complex, East Griqualand. *Trans. Roy. Soc. South Africa*, xxxi, 83–110.

ROEVER, W. P. DE, 1942. Olivine-basalts and their alkaline differentiates in the Permian of Timor. *Geological Expedition to the Lesser Sunda Islands*, iv, 213–289.

SARGENT, H. C., 1917. On a spilitic facies of the Lower Carboniferous lava-flows in Derbyshire. *Quart. Journ. Geol. Soc.*, lxxiii, 17–23.

SCOTT, BERYL, 1951a. A note on the occurrence of intergrowth between diopsidic augite and albite, and of hydrogrossular from King Island, Tasmania. *Geol. Mag.*, lxxxviii, 429–431.

—— 1951b. The petrology of the volcanic rocks of south east King Island, Tasmania. *Proc. Roy. Soc. Tasmania*, 1950, 113–136.

SHANNON, E. V., 1924. The mineralogy and petrology of intrusive Triassic diabase at Goose Creek, Loudoun County, Virginia. *Proc. U.S. Nat. Mus.*, lxvi, 1–86.

SUNDIUS, N., 1915. Beiträge zur Geologie des südlichen Teils des Kirunagebiets. *Geologie des Kirunagebiets* 4. Uppsala.

—— 1930. On the spilitic rocks. *Geol. Mag.*, lxvii, 1–17.

TOMKEIEFF, S. I., 1941. Metasomatism in the basalt of Haddenrig quarry near Kelso and the veining of the rocks exposed there. *Miner. Mag.*, xxv, 45–59.

TURNER, F. J., 1948. Mineralogical and structural evolution of the metamorphic rocks. *Geol. Soc. Amer. Mem.*, xxx.

TURNER, F. J., and J. VERHOOGEN, 1951. *Igneous and metamorphic petrology*. New York, McGraw Hill.

TUTTLE, O. F., and N. L. BOWEN, 1950. High-temperature albite and contiguous feldspars. *Journ. Geol.*, lviii, 572–583.

VINCENT, E. A., 1950. The chemical composition and physical properties of the residual glass of the Kap Daussy tholeiite, east Greenland. *Miner. Mag.*, xxix, 46–62.

—— 1953. Hornblende-lamprophyre dykes of basaltic parentage from the Skaergaard area, East Greenland. *Quart. Journ. Geol. Soc.*, cix, 21–47.

WALKER, F., 1935. The late palaeozoic quartz-dolerites and tholeiites of Scotland. *Miner. Mag.*, xxiv, 131–159.

—— 1952. Differentiation in a quartz dolerite sill at Northfield Quarry, Stirlingshire. *Trans. Edin. Geol. Soc.*, xv, 393–405.

WALKER, F., and A. POLDERVAART, 1949. Karroo dolerites of the Union of South Africa. *Bull. Geol. Soc. Amer.*, lx, 591–706.

WALKER, F., H. G. C. VINCENT, and R. L. MITCHELL, 1952. The chemistry and mineralogy of the Kinkell tholeiite, Stirlingshire. *Miner. Mag.*, xxix, 895–908.

WELLS, A. K., 1923. The nomenclature of the spilitic rocks. Part II. The problem of the spilites. *Geol. Mag.*, lx, 62–74.

YODER, H. S. (Jr.), 1952. The MgO–Al_2O_3–SiO_2–H_2O system and related metamorphic facies. *Amer. Journ. Sci. Bowen Volume*, 569–627.

DEPARTMENT OF GEOLOGY,
KING'S COLLEGE,
NEWCASTLE-UPON-TYNE.

EXPLANATION OF PLATE V

FIG. 1.—Cervicorn augite in spilite (6203), Hapuka Crag, Great Island, Three Kings Group. Ordinary light, × 33.

FIG. 2.—Radiating groups of augite crystals, microphenocrysts of albite and interstitial pools of chlorite in spilite (6209), Tasman Valley Great Island. Ordinary light, × 78.

FIG. 1.

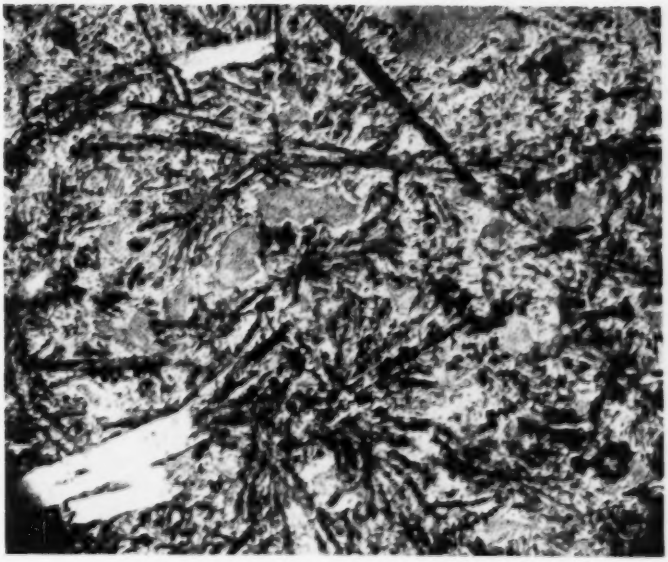


FIG. 2.

SPILITES FROM NEW ZEALAND.

Tectonic Facies, Orientation, Sequence, Style, and Date

By W. B. Harland

Abstract

Some essential features of the general tectonic description of a region are outlined under the above heads. Tectonic style is the product of facies and orientation in their distinctive sequence, and is assumed to be independent of date. A type of tectonic sequence is outlined from Ny Friesland, Spitsbergen, with a distinct late stage elongation along the fold axes.

I. Introduction

In writing a tectonic account [1] of the orogenic belt of Ny Friesland, Spitsbergen, I was struck both by the analogous problems in the Caledonides elsewhere, and by the difficulties which seem to have arisen therein partly from the complexity of tectonic processes and partly from the confusion of concepts and conventions. It is hoped that this paper may serve to distinguish some underlying concepts and also to further an agreed use of developing conventions. An example from Spitsbergen is drawn upon to illustrate the complexity of tectonic processes even in a relatively simple structure. It is, however, my intention to separate the general discussion of principles in this paper from their detailed application in a forthcoming regional study.

II. Tectonic Facies

Facies has long been a convenient term for the sum of characters (whatever they be) deriving from a particular environment or set of conditions. " Facies " alone is already in need of qualification except when its context makes this unnecessary. Therefore the simple extension of its use as developed here would not seem to affect its accepted usage ; indeed it has already been so used (Kennedy, 1955). The tectonic facies of different rock masses may differ by virtue of the different tectonic conditions (whatever they be) which have produced the features observed. Whether or not it be possible to infer distinctive sets of physical conditions it is clear that varying conditions have produced distinctive structures. So long as geological observations have been made structures have been described, often very fully and in great variety. A proper description of tectonic facies should include at least the three related aspects of *form*, *scale*, and *composition*. In so far as these are dependent variables the omission of one reduces the value of the other aspects described.

Form is a geometrical property and includes the simpler elements of structure explicitly defined with a series of structural terms such as

[1] Sedgwick Essay for 1955 (September, 1954). The Structural History of N.E. Vestspitsbergen.

comprise the basis of most books on structural geology (fold structures, fracture structures, etc.). Form also includes that additional quality or style of form more easily depicted as in a profile. " Tectonic Style " has already been used in this sense but when so used it has usually implied the fuller meaning reserved to it below (e.g. McIntyre, 1951).

The *scale* of a structure is a simple measure to observe although the theory of dimensions long known to physicists has far too recently come to play a part in tectonic thinking (as argued by Hubbert, 1937). This is commonly accepted in the design and interpretation of experiments with geological models. It is not so generally applied in the interpretation of geological structures where, for instance, the contrasting scales of similar forms imply different conditions of deformation. Thus similar forms found in " slump ", glacial, salt, and nappe structures reflect different conditions of formation by their different scales alone and therefore different tectonic facies. The deliberate attention to scale serves to underline the connection between form and composition.

Composition or the nature of the material involved controls the mode of deformation. A given lithological facies deformed to a particular shape and size sets limits to the conditions of deformation which may be inferred. The study of metamorphic facies explores this field from a mineralogical point of view for more extreme conditions, but the petrophysical characteristics of sedimentary and igneous rocks are important too in conditions of less intense deformation. It is the particular value of the portmanteau term *facies* that the necessary characters are implied even though their precise nature or cause may not be understood or even suspected.

Tectonic composition like form may involve a complex of simpler elements. Thus a series of rocks folded together showing a combination of relatively competent and incompetent members may have been formed under uniform conditions and so comprise one facies within which variations of composition are adjusted by variations of form and/or scale. In the first instance more facies will be described than are necessary in a final interpretation but so long as the facies are labelled by their observed characters no confusion will arise with facies labelled by inferred conditions.

III. Tectonic Orientation

The orientation of a structure may be independent of the other variables and is conveniently distinguished from facies. Many different sets of orthogonal co-ordinates have been used and some of these are discussed below.

Sander's use of *a*, *b*, and *c* (Phillips, 1937, and Cloos, 1946, p. 5) has been broadly followed but there are difficulties in the routine use of

these axes. There is rarely doubt about *b*, the direction parallel to the fold axis, since it is a general rule (Pumpelly's) that syngenetic major and minor folds have parallel axes. There may, however, be difficulty with *b* and more frequently with *a* since the movement plane (*ab*) is a genetic concept not applicable to every case. To avoid making such a kinematical interpretation purely geometrical, co-ordinates at two-scales have been used (*a*, *b*, *c* and *A*, *B*, and *C*).

A recent paper (Williamson, 1955) illustrates the difficulty arising from using *a*, *b*, and *c* in a kinematical sense. In a three dimensional motion, which is the direction of transport ? Anderson (1948) argues similarly that the *b* axis, distinctive in monoclinic symmetry, is liable to be confused in an approximation to orthorhombic symmetry.

Shear axes p, *q*, and *r* have been clearly defined by Anderson (1948, p. 106) for a case of simple shear when *p* is the direction of shear or gliding, *pq* the plane of gliding, and *pr* the plane of deformation. This notation carries some of the advantages of Sander's concept and there is little confusion in this part of the alphabet. However, this use applies only to a restricted type of deformation and requires more knowledge of it than is commonly obtained at first. Consequently the axes are of value in discussion of conclusions but not for primary reference.

Fabric axes a, *b*, and *c* refer to specimens in the laboratory (Fairbairn, 1942, p. 5, and Billings, 1942, p. 336). *b* is the direction of dominant lineation and if there be some crenulation this may be taken as dominant. *ab* is the plane of schistosity or dominant foliation. Some discretion may still be necessary in choosing directions but the choice is of arbitrary axes for reference and not for fundamental classification. "*b*-lineations" are in this sense meaningless in so far as they are by definition inevitable. Sander's *b* would generally parallel such lineations with similar implications. The purpose of these axes is to relate various microscopic or megascopic directions to a specimen rather than to define a lineation. These axes need not remain parallel in neighbouring specimens in the field.

Regional axes A, *B*, and *C*[1] refer to co-ordinates chosen from field study. *B* is the horizontal trend of fold axes on a larger scale and *A* is usually taken as horizontal. *A*, *B*, and *C* are thus regional co-ordinates, and plunging fold axes may be indicated by *B'* and *C'*. *A* is a direction derived from the choice of fold axes without necessarily implying a direction of transport or plane of movement, which in any case need not be horizontal. Where there is a pronounced structural trend the use of these regional tectonic co-ordinates is usually preferable

[1] *H*, *L*, and *V* have been used but might not be acceptable as applied to lineations, whereas *A*, *B*, and *C* would apply with little change to much existing literature.

to geographical co-ordinates in relating and describing the various structural directions; and they can be used without begging kinematical questions. Thus, for instance, lineations may be found commonly in *B*, often in various directions in the *AC* plane, and occasionally oblique to it.

There may still be an arbitrary element of choice which increases considerably if there is no one obvious direction for *B*. In any case the directions chosen should be stated at the outset.

Strain axes [1] *X*, *Y*, and *Z* are the three diameters, minimum, intermediate, and maximum respectively, of the strain or form ellipsoid. The *strain ellipsoid* refers properly to the dimensions of an elastically deformed sphere before rupture and not to plastic deformation which should be described by a form ellipsoid. However, strain ellipsoid is used loosely (Leith, 1937) and without serious confusion. Indeed its main value in tectonics is to approximate the bulk structure whether it possesses orthorhombic or monoclinic symmetry or less. Usually the direction of bulk shortening *X* and bulk elongation *Z* will be indicated without any quantitative assessment of the three diameters. Some quantitative estimate can sometimes be hazarded and instances of (uni)axial symmetry would be accommodated by $X = Y$ (prolate), and $Y = Z$ (oblate). The strain ellipsoid is ideally suited to the description of pure strain in the deformation of homogeneous masses usually on a smaller than regional scale.

Stress axes [2] *x*, *y*, and *z* are the directions in the general case of the three principal stresses (σ_1, σ_2, and σ_3) respectively maximum, intermediate, and minimum. In tectonic problems actual values for the principal stresses will seldom be obtainable so that the use of these axes is simply to orientate the maximum and minimum stress with the additional possibility of noting whether the magnitude of the third stress appears to have been intermediate or approximates to the maximum or minimum stress.

The relation between the stress and strain ellipsoids is not straightforward. Assuming uniform plastic deformation, *x*, *y*, and *z* would parallel *X*, *Y*, and *Z*. But if deformation were primarily by simple shear, Anderson's shear directions *p*, *q*, and *r* would lie with *q* parallel to *y* but *p* and *r* somewhere between *x* and *z*. Thus elongation (*Z*) would tend to lie in the direction of shear (*p*) or tectonic transport, and locally it must be so for this type of deformation. Considered regionally, however, the bulk elongation (*Z*) will tend towards the minimum stress direction (*z*) either by the diminution of the angle *pz* in more

[1] Nevin (1949) used *A'*, *B'*, *C'*, Fairbairn (1942) Billings (1942) and Turner (1948) used *C*, *B*, *A*.
[2] Nevin (1945) used *A*, *B*, *C*.

plastic material or on a larger scale by the averaging of deformation structures.

Although there is a general tendency for X, Y, and Z to parallel x, y, and z at a given time, a variety of effects may be produced in different facies. The strain observed may well be the product of a succession of changing stress systems. In any case a tectonic problem requires the analysis of strain before any stress inference can be made and because of these uncertainties the strain ellipsoid concept is generally preferable for correlating structures, and this was Leith's advice in 1937.

Genetic classification

In spite of the above difficulties the stress orientation over large areas appears to have persisted for periods sufficiently long to produce a variety of related structures. Following Anderson's classic analysis of faults (1905, 1942, and 1952), for example, there are three simple conditions of faulting : thrust faulting, wrench faulting, and gravity faulting with the directions of minimum, intermediate, and maximum stress (z, y, and x) respectively vertical. These three classes of distinctively orientated stress may be extended to classify and relate other deformation structures such as folds, joints, cleavage, flowage, and igneous flow. It would require another paper to apply this classification in detail but by analysis of the strain orientation of such structures the approximate stress orientation is inferred and structures if synchronous may be genetically related.

In so far as the principal stresses approximate to vertical and horizontal directions these three orientation regimes and their derivatives account for most structures. A tectonic couple, however, may result in other orientations even of large scale structures. Moreover, throughout a large structure there is bound to be a variation in both orientation and magnitude of the stresses and particularly in the neighbourhood of any important boundary such as the topographical surface (Hafner, 1951). In other circumstances the distinctiveness of the directions of principal stresses may be weakened by an approximation to axial or even isotropic symmetry. Finally, as pointed out above, any structure is the product of a succession of varying stress conditions so that the strain ellipsoid (X, Y, Z) is the sum of successive ellipsoids (X_1, Y_1, Z_1, + X_2, Y_2, Z_2, + . . .) possibly all differently orientated.

IV. Tectonic Sequence

Stress conditions vary continuously in space and in time and it may be difficult from a purely static or geometrical interpretation (epitomized in a strain ellipsoid) to disentangle the stages by which the structure comes into being.

In the component field of metamorphic studies it is clear that the

time during which any set of conditions obtained determines the effect it has had on the total facies in relation to other conditions. The order in which these take place also determines the product.

A structure may represent a sequence of movements according to two or more patterns. This is to be expected when successive orogenies with different orientation are superimposed one on the other. Although these may be unwound backwards in time they may be confused with cases where a single "cause" or the operation of "one" orogeny produces a sequence of diverse structures. Recent examples of this sort of difficulty are described by Reynolds and Holmes (1954) and King (1955).

The diversity of possible structures arising from the continued operation of one orogeny may be illustrated by considering a region of flat-lying rocks subjected to horizontal compression ; that is to say, the deformation of the ideal geosyncline.

At first, as the horizontal component of stress increased (aided by any decrease in strength along the prism of rock), deformation would take place with the minimum principal stress vertical. Faulting, folding, and at depth flowage would occur, all of thrust type orientation, that is with the bulk extension upwards and downwards (*A*, *B*, *C*, parallel to *X*, *Y*, *Z*). The strike of the structure with well defined fold axes will accentuate any previous elongation of the geosyncline, or even introduce it and result in a clear regional orientation. So far a relatively rigid lateral constraint is assumed and there will be no change of dimension in this direction (*B* and *Y*). The kinematics of folding will be represented entirely in the movement plane which is a plane of monoclinic symmetry. Such a structure is suitably depicted in a series of transverse sections or profiles in the *AC* plane. A variety of such structures in the same orientation class is shown in Wilson's admirable Tintagel diagram (1951, fig. 10).

Any *B* lineation in this structure will be due to folding, rotation, or rolling, or the effects of intersection of surfaces such as cleavage and bedding. Any "a" lineation will lie in the *AC* plane following the fold curves or maintaining a constant plunge (*pA*) for some distance where large scale shearing has taken place.

Deformation at depth may be highly complex giving the impression of turbulence but it will nevertheless tend to be two dimensional, being represented in a series of movement planes.

This first stage of compression may take place in several phases or pulses and the compressive movements might then be "exhausted". In this case the structure if stable will be preserved. At any time, and perhaps continuously through such movements a surface relief might develop sufficiently high to create gravity conditions (*x* parallels *C*) with local or even regional instability. The compensating outward

flow, unilateral or bilateral, would assume a series of fold and fault forms continuous with those below. This is not to say that all gravity tectonics have a compressive origin.

Consider now such a case when the compression is not exhausted but continues to pile up an orogenic welt. If this be continued there may come a time, different at different levels, when the weight of the overburden exceeds and overcomes the lateral constraint. The vertical stresses, inevitably less than the compressive stresses would thus equal or surpass the lateral stress.

In the first instance when the vertical stress approaches the lateral stress ($z \rightarrow y$) radial extension in a plane perpendicular to the main compression may follow. Given pelitic facies, slaty cleavage may develop. This does not mean that all slaty cleavage possesses radial symmetry for apart from the bedding which intersects it giving a *B* lineation, a marked elongation may be detected by distorted fossils, extended pebbles, or concretions. Such is the net result of all the flowage which may or may not have involved radial flow. It is not implied that radial flow would necessarily show any radial orientation of particles. A flattening with axial symmetry would be sufficient evidence if there were no equivalent decrease in volume.

With increasing overburden, or at greater depth, a larger proportion of material would be driven sideways rather than upwards. Wrench or tear conditions thus obtain (with *x*, *y*, and *z* respectively parallel to *A*, *C*, and *B*) but the resulting structures will be superimposed on existing structures due to thrust conditions. These merge imperceptibly into true axial flow with extension along *B* and compression perpendicular to it with a plane of axial symmetry (*AC*).

Axial flow or Einengung (Sander, 1948) is difficult to distinguish from the effects of wrench flow and indeed the two may be taken together, each possessing evidence for elongation in *B*, often characterized by a marked lineation in that direction.

An example of axial flow was clearly described by Weiss (1954) from a roof pendent without firmly established external tectonic relations.

The deep metamorphic belt of the Ny Friesland mountains in Spitsbergen illustrates a similar style of deformation extending for some tens of miles and related broadly in space and time to neighbouring structures. Deformation took place under a great stratigraphical and tectonic load. There is no doubt about a considerable elongation in *B* marked by a distinctive lineation in the grain of the rocks, but proved by widespread and constant boudinage. The whole is an apparently uniform homoaxial structure. The boudinage is a late stage in the elongation often fracturing previous flow structures and the displacements of these fractures reveal wrench conditions and gravity conditions in different circumstances each resulting in a lengthening

along the fold axes (*B*). In still deeper tectonic facies the lengthening appears to have taken place entirely by flow. It can be demonstrated that the elongation along the fold axes has taken place at a late stage and in part at least subsequent to the deformation by flow folding. In this deepest zone any lineation which may have accompanied the folding and rotation has been superseded by the lateral elongation.

It has been generally agreed that in the first stages of deformation extension will be in a movement plane containing the direction of compression, and superficially, at least, shear structures due to Anderson's (1948) canal motion may be encountered. Simultaneously at depth, or at a later stage folding may produce a rotational effect with lineation parallel to the fold axes (due to intersection of fracture surfaces or deeper still to flow orientation). The whole of this first stage may be essentially two dimensional with thrust orientation.

It has not been so generally recognized that a further wrench orientated class of deformation culminating in axial flow may develop at depth with elongation in the direction of the fold axes. Evidence for such movements may not have been so interpreted because of the difficulty of accounting for a regional elongation in *B*. However explained, in the author's opinion this must be reckoned a normal process and the sequence outlined above and illustrated by the Ny Friesland orogeny is thought to be typical of many orogenic structures. Many other sequences are possible and considerable variation of sequence may be demonstrated in different parts of the same major structure; but the above would seem to be one of the simplest sequences for a major orogenic belt.

V. Tectonic Style

Tectonic style is taken as the product of facies and orientation in their peculiar sequence. The sequence and duration of successive stress and temperature conditions on a variety of rock types will give a distinctive facies and the sequence and duration of successive stress orientations will at the same time give this facies its distinctive style. The pattern produced by the various stress arrangements rather than a classification by geographical directions is implied here.

Whereas in the above discussion only a limited number of ideal stages were enumerated, a great variety of transitional movement patterns must be taken into account. Complex three dimensional movements may then result from changing stress orientation in a uniform mass to which must be added the effects of couples due to the heterogeneity of the earth's crust. All combine to give a characteristic style to the whole.

Such a conception of style follows the implications of earlier use of the term, though frequently insufficient information is given to charac-

terize its various aspects. So many variables indeed are compounded that it would be almost impossible to isolate, define, and account for each. Increasingly, however, more complete tectonic descriptions are available giving profiles, petrology, fabric, and tectonic setting. Thus individual type examples will for some time serve as labels until, if ever, an empirical classification into species is attempted. A recent paper (Weiss, McIntyre, and Kursten, 1955) illustrates this use and gives references to a succession of similar papers.

Within such an apparently endless series of possibilities it is encouraging to find already marked similarities of style formed at different times and places so that an eventual correlation with crustal movement patterns of limited type may be envisaged.

VI. Tectonic Date

We assume that the date or age of earth movements is a factor independent of what makes tectonic style. It is not impossible, however, that some relationship can be established. This is more likely in contrasting styles of earlier and later stages in the development of the earth's crust.

The actual dating of orogeny is subject to what may be called the Principle of Tectonic Uncertainty. Whereas a small disturbance may be dated very precisely within its stratigraphical succession, in general the larger the disturbance the greater the unconformity. Put another way, the more we know of the structure and sequence of movement or style of a system the less certainly do we know its dates.

As the unconformity narrows away from an orogeny a closer knowledge of the time of the phase or pulse may be obtained and this has tempted many to find some pattern of earth movement dated far more precisely than is warranted. The full sequence of an orogeny may well extend in a continuous series of movements of which only particular phases leave their mark in the stratigraphical record. Uniform uplift and subsidence extending over a long period may well leave a stratigraphical discontinuity giving the impression of relatively sudden changes.

There is more wisdom than the obvious caution in dating movements by the outside time limits determined stratigraphically on the spot ; for the fundamental mechanism of earth movements as well as the sedimentary and erosional history need to be known and related.

VII. Acknowledgments

The idea of the relation between tear faulting and axial flow following as a possible later and deeper stage on thrust conditions was stimulated by Professor O. T. Jones's lectures in 1937. The observations in Spitsbergen will be described in more detail and are the result of a

number of expeditions since then which I owe to many friends and institutions. This debt will be acknowledged more fully when the observations are described in detail. Finally I wish to thank Dr. F. C. Phillips who in 1937 introduced me to the concepts of orientation and fabric and who again recently read the manuscript and kindly suggested several improvements. The choice of conventions is my responsibility, however, and is made in some knowledge of the difficulties which attend this scheme and indeed seem to follow any scheme.

VIII. REFERENCES

ANDERSON, E. M., 1905. The Dynamics of Faulting. *Trans. Geol. Soc. Edinb.*, viii, 387–402.

—— 1942 and 1951. *The Dynamics of Faulting*. London.

—— 1948. On lineation and petrofabric structure. *Quart. Journ. Geol. Soc. London*, civ, 99–126.

BENIOFF, H., 1954. Orogenesis and deep crustal structure. *Bull. Geol. Soc. Amer.*, lxv., 385–400.

CLOOS, E., 1946. Lineation. *Mem. Geol. Soc. Amer.*, xviii.

FAIRBAIRN, H. W., 1942. *Structural Petrology of Deformed Rocks*. Cambridge, Mass.

HAFNER, W., 1951. Stress distributions and faulting. *Bull. Geol. Soc. Amer.*, lxii, 373–398.

KENNEDY, W. Q., 1955. The tectonics of the Morar anticline and the problem of the North-West Caledonian Front. *Quart. Journ. Geol. Soc. London*, cx, 357–390.

KING, B. C., 1955. The tectonic pattern of the Lewisian around Clashnessie Bay near Stoer, Sutherland. *Geol. Mag.*, xcii, 69–80.

KVALE, A., 1953. Linear structures and their relation to movement in the Caledonides of Scandinavia and Scotland. *Quart. Journ. Geol. Soc. London*, cix, 51–73.

LEITH, A., 1937. The Strain ellipsoid. *Amer. Journ. Sci.*, xxxiii, 360–368.

MCINTYRE, D. B., 1951. Note on the Tectonic Style of the Ord Ban Quartzite. *Geol. Mag.*, lxxxviii, 50–4.

NEVIN, C. M., 1949. *Principles of Structural Geology*. New York.

PHILLIPS, F. C., 1937. A Fabric Study of some Moine Schists and associated rocks. *Quart. Journ. Geol. Soc. London*, xciii, 581–620.

REYNOLDS, D. L., and HOLMES, A., 1954. The superposition of Caledonoid folds on an Older Fold System in the Dalradians of Malin Head, Co. Donegal. *Geol. Mag.*, xci, 417–444.

SANDER, B., 1948. *Einführung in die Gefügekunde der geologischen Körper*. Innsbruck.

TURNER, F. J., 1948. Mineralogical and Structural Evolution of the Metamorphic Rocks. *Mem. Geol. Soc. Amer.*, xxx.

WEISS, L. E., 1954. A study of Tectonic Style : Structural investigation of a marble-quartzite complex in southern California. *Univ. Calif. Publications in Geol. Sciences*, No. 30, 1–102.

WILLIAMSON, W. O., 1955. Lineations in three artificial Tectonites. *Geol. Mag.*, xcii, 53–62.

WILSON, G., 1951. The Tectonics of the Tintagel Area, North Cornwall. *Quart. Journ. Geol. Soc. London*, cvi, 393–432.

WEISS, L. E., MCINTYRE, D. B., and KÜRSTEN, M., 1955. Contrasted Styles of Folding in the Rocks of Ord Ban. *Geol. Mag.*, xcii, 21–36.

The Origin of Garnets in the Borrowdale Volcanic Series and Associated Rocks, English Lake District.

By R. L. Oliver.

(PLATE VI)

Abstract

Almandine-rich garnets occur as euhedral crystals in extrusive and intrusive rocks which range in composition from 59 per cent. to 70 per cent. SiO_2. Eight complete garnet analyses (major and trace elements) indicate a small variation in composition which, together with corresponding variation of physical properties, appear to correlate with the mineralogical composition of the containing rock. Field, microscopic and chemical evidence suggests, on balance, that the garnets are pyrogenetic. Magmatic conditions suitable for the crystallisation of almandine-rich garnet are discussed.

Introduction

In the following paper, discussion is restricted to a consideration of the garnets in virtually unmetamorphosed lavas, tuffs, and intrusive rocks of widespread aereal and stratigraphic distribution in the Lake District; the writer is not concerned with the undoubted contact garnets found in the Skiddaw Granite aureole (e.g. Rastall, 1910), on Carrock Fell (e.g. Hollingworth, 1937), and in the Shap Granite aureole (e.g. Harker and Marr, 1893).

The most garnetiferous extrusives of the Borrowdale Volcanic Series (of Ordovician age) are the so-called "streaky rocks" (Marr, 1900; Walker, 1904; Green, 1915), known also as the Sty Head Garnetiferous Group (Marr, 1916). These rocks outcrop most prominently in the central mountain district (where they have recently been remapped by the writer as the Airy's Bridge Group), but appear also further east in the Haweswater area (see Marr, 1916, fig. 5; though cf. Green, 1915, p. 208). They are dacitic, rhyodacitic, and rhyolitic lavas, welded tuffs and more normal pyroclastics. Much of Hartley's (1932; 1942) sparsely garnetiferous "intrusive" (quotation marks by the writer) rhyolite in the Langdale and Helvellyn regions probably belongs here (see also Walker, 1904, p. 91; and Marr, 1916, fig. 5). Welded tuffs with garnets are not restricted to the Airy's Bridge Group, but occur also (at least in the central mountain district) at higher stratigraphic levels.

Other garnetiferous extrusive rocks are the andesites and associated tuffs at Stonethwaite, Borrowdale (Walker, 1904, fig. 2), and those of the Falcon Crag group, east of Derwentwater (Walker, 1904); and garnet-bearing andesites are present also in the Haweswater area, closely associated with the streaky "rocks" already mentioned (Walker, 1904; Green, 1915). More recently, Hadfield and Whiteside (1936)

have recorded garnets in the andesites of High Rigg, south-east of Keswick.

Garnetiferous minor intrusions are described by Walker (1904) under the headings: the intrusive complex of Blea Crag, Langstrath; intrusions in the Bowfell district; basic offshoots from the Eskdale Granite (a range of basic to acid rocks is included here); the intrusive complex of Burtness Combe, Buttermere; other garnetiferous intrusions in the Lake District. The last section includes the familiar Armboth Dyke which outcrops west of Thirlmere, and also a number of acid garnet-bearing dykes of widespread occurrence. The age of these minor intrusions is uncertain. Some, in the vicinity of the Eskdale granite, appear to be related to this intrusion (of Devonian age?), but some possess features in common with the Borrowdale volcanics, not the least important of which is the presence of the garnets themselves.

The microgranites of Threlkeld and Low Rigg, east of Keswick, are among the larger intrusive bodies which contain garnets (see, for example, Hadfield and Whiteside, 1936), and another is the "granodioritic" (Trotter, *et al.*, 1937) variety of the Eskdale granite. In the more extensive pink Eskdale muscovite granite, garnet has been found only in the heavy residues (Rastall and Wilcockson, 1915). The Haweswater dolerite (Hancox, 1934) also contains garnets.

In the stratigraphic succession garnets are, with limited exceptions, characteristic of certain horizons and not of others, over a strike distance of several miles. Garnets are generally present indiscriminately in rock lapilli and as single crystals in the finer matrix of the tuffs. In some essentially non-garnetiferous pyroclastics, occasional garnets may be confined to one or two rock fragments. Garnetiferous dykes commonly trangress country rock which is completely non-garnetiferous. The writer does not agree with Green's (1915) inference that garnet is associated with pyrite to any significant extent, and considers a coincidence the fact that the only garnetiferous rock found on High Rigg, south-east of Keswick, is one which also contains pyrite (see Hadfield and Whiteside, 1936, p. 57).

The distribution of the garnets concerned in the Borrowdale volcanics generally does not appear to be related to the outcrop of the several large intrusions. This is noticed by Green (1915) with respect to the Eskdale granite. Green suggests that the garnets "have some preference for the neighbourhood of minor intrusions", but the present writer cannot confirm this. Harker (discussion to Walker, 1904, p. 105) considers that their distribution is suggestive of a regional metamorphic origin, though none of the Lake District volcanics, outside the thermal aureoles, represent anything higher than the lowest subzone of the green schist metamorphic facies.

Sorby had long ago (1880) expressed the view that the garnets of

Lake District ash are original constituents, and a similar paragenesis for the "streaky" rock garnets was first suggested by Marr (1900), though he later concludes that they are metamorphic. Harker also appears to have vacillated, for he had earlier (than 1904, as noted above), in 1902, expressed the opinion that the garnets in tuffs are of secondary origin and those of intrusive rocks are primary. Hutchings (see Walker, 1904, p. 105) maintained that the garnets are metamorphic.

Midst this plethora of ideas it is noteworthy that detailed and comprehensive work by Walker (1904) specifically on the garnetiferous and associated rocks of the Lake District led him to the conclusion that the garnets, at least in the intrusive rocks, are pyrogenetic.

TEXT-FIG. 1.—Garnetiferous xenolith in rhyolite, Rosthwaite Fell. The xenolith is thought to be earlier "Borrowdale" material. Plain polarized light. × 22.

More recently, Green (1915) associates the formation of garnets with the development of the "streaky" texture, characteristic of much of the Sty Head Garnetiferous Group (though he notes the presence of garnets also in a wide variety of other rock types), attributing both[1] to the agency of "circulating solutions under high hydrostatic pressure", probably during the solfataric stage of the Borrowdale volcanic episode. Hartley (1932), Hancox (1934), and Hadfield and Whiteside (1936) come to similar conclusions concerning garnets in the Langdale rhyolite, the Haweswater Dolerite, and the andesites of High Rigg respectively.

PETROGRAPHY

In the central mountain district, garnet crystals are best formed, as well as being most common, in welded tuff and in dacite, near the top

[1] The "streaks" are thought by the writer to represent both flow banding in lavas and compressed fragments in welded tuff (see Oliver, 1954).

of the Airy's Bridge Group. Well-developed rhombic dodecahedra (110), icositetrahedra (211), and combinations of the two are found up to ¼ inch diameter—a "tendency to perfect crystalline form" which is noticeable also in "the eastern Lake District" (Green, 1915, p. 213). In general, however, garnets are smaller, and crystal facets often not developed, though they are nevertheless invariably phenocrystic in the lavas and lava fragments.

Inclusions of iron ore, as minute particles or as blebs up to 0·2 mm. across, are common. Apatite crystals, averaging 0·4 × 0·013 mm., also may be present and, less frequently, zircon. During separation of the garnets for analysis, the iron ore was found to have a similar magnetic intensity to that of the garnets, and is, therefore, probably ilmenite.

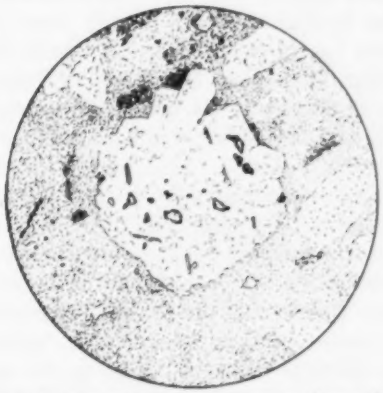
TEXT-FIG. 2.—Corroded garnet associated with iron ore in glomeroporphyritic altered plagioclase; rhyolite, Rosthwaite Fell. Plain polarized light. × 49.

Walker (1904, p. 102) notes that alteration to chlorite, with separation of iron ore, is the most frequent change that the Lake District garnets undergo, though in the predominantly dacitic and rhyodacitic rocks of the central mountain district, this is not common. Such alteration is more characteristic of garnets from andesitic rocks, a fact which is perhaps related to the apparently high MgO and low MnO contents of these garnets compared with those from more acid rocks (see p. 133, and also Ramberg, 1952, fig. 32).

Many of the garnet crystals exhibit nondescript shapes, and appear to be discrete fragments (see also Walker, 1904, p. 87); these are contained in lavas, but more frequently in tuffs. In a rhyolite from Rosthwaite Fell, the broken edge of a xenolithic fragment is contiguous with

that of included garnet, thus suggesting that the latter was contained in the xenolithic rock prior to fracture (see Text-fig. 1). The xenolithic rock is a tuff which most likely has been derived from an earlier garnetiferous tuffaceous member of the Borrowdale Series.

Commonly, the garnets are surrounded by, or intergrown with, euhedral plagioclase which is identical in form and composition with the feldspar phenocrysts elsewhere in the rock[1] (Plate VI, Figs. 1 and 2, Text-figs. 2 and 3); (see also Walker, 1904, plate 13, 1, and plate 14, 4; and Green, 1915, fig. 1). Consideration of a number of garnet-feldspar clusters indicates that the proportion of garnet to feldspar varies inversely, suggesting that one has grown at the expense of the other.



TEXT-FIG. 3.—Garnet remnants, with zircon and apatite, in glomeroporphyritic altered plagioclase; welded tuff, Grain Gill. Plain polarized light. × 66.

Very occasionally garnet contains, and completely surrounds, the feldspar.

Walker (1904, p. 94) considers that the manner of association of the two minerals, in intrusive rocks, is indicative of a primary magmatic origin for the garnet, and that the feldspar has been formed "by the action of still liquid matter on the garnet". Green (1915), on the other hand, strongly maintains that the garnet has been formed hydrothermally as the result of interaction of pre-existing feldspar and included iron ore.

Consideration merely of the garnet-feldspar relationship, as illustrated, is not likely to indicate the validity of one or other of these

[1] For example, in an andesite from near Stonethwaite, Borrowdale, plagioclase intergrown with garnet is An_{58}; the phenocrysts elsewhere in the slide are An_{59}. In a rhyodacitic welded tuff from Low Saddle, near Blea Tarn, plagioclase surrounding garnet is An_7; phenocrysts elsewhere in the slide are An_{4-8}.

beliefs. The very examples used by Walker to illustrate his contention, are later considered by Green (1915) pp. 212–213, to support the hydrothermal hypothesis. It is thought by the present writer, however, that Green's theory, if justified, would be supported by evidence such as the presence of garnet reaction zones between iron ore and feldspar, as, for example, in some of the charnockitic rocks from Reinstraid, Sutherland (e.g. Slide No. 74561),[1] and as described by Shand (1945). Also, it seems unlikely that the presumed catalytic action of hydrothermal water vapour would almost invariably facilitate commencement of the reaction plagioclase + iron ore → garnet in the middle of the feldspar phenocryst or cluster of phenocrysts.

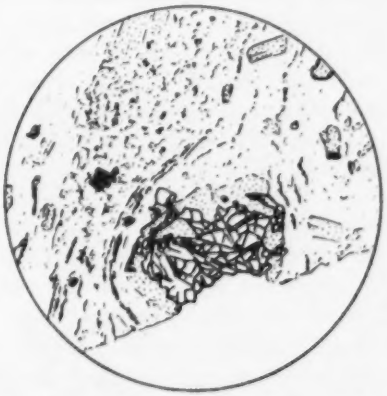
A rather different feldspar corona of comparatively small, closely-packed plagioclase crystals, arranged radially round the garnets is a feature of intrusive "porphyrite" from Langstrath (Slide No. 77227; and see also Walker, 1904, plate 13, 2), and of "quartz porphyrite" from near Peers Gill (Walker, 1904, p. 80). This feature is considered by Walker (p. 74) to point to "the early consolidation of the garnet from the molten mass", around which, as a nucleus (in the present writer's opinion), the feldspar appears to have crystallized, as it has (in one of the Langstrath examples) also round earlier phenocrysts of feldspar and quartz. A similar genetic relationship may exist in a rock from Bleaberry Fell (Slide No. 3829), where both garnet and chlorite pseudomorphs after pyroxene (?) are enclosed by plagioclase.

Garnets, surrounded by a feldspar corona, occur in Devonian rhyodacites from Victoria (Edwards, 1936, p. 41 and fig. 1). The feldspar is orthoclase and albite-oligoclase, considered by Edwards to be "'reject matter' from the magma and crystalline material out of which the garnet was formed". This is indicated, according to Edwards, by the fact that the width of the feldspar rim varies directly with the size of the garnet, contrary to the situation in the Lake District rocks. A more comparable illustration of the garnet-feldspar relationship in some of the Lake District rocks is perhaps the graphic intergrowth of these minerals in the Dartmoor granite, considered by Brammall and Bracewell (1933) to be of pyrogenetic origin. The "atoll" garnets, with feldspar "lagoons", present in some strongly metamorphosed rocks (e.g. Williamson, 1935) bear a superficial resemblance to some of the Lake District examples of feldspar surrounded by garnet, though there is probably little, if any, genetic significance in the similarity.

Garnets with plagioclase corona have been seen by the writer in lavas, intrusive rocks, and welded tuffs, but not in the more strictly pyroclastic rocks of the mapped area. Walker (1904, p. 94), however, records two instances of this feature in (unwelded) tuffs overlying the

[1] Slide and specimen numbers are those in the collection of the Department of Mineralogy and Petrology, Cambridge University.

"streaky rocks", and considers these occurrences to be evidence (contrary to his opinion, noted above) against the primary origin of the garnets and their incorporation in the tuffs as discrete fragments; the crystals of the corona, which "often show very perfect crystal outlines, with sharp and deep re-entrant angles between contiguous feldspars", are thought too susceptible of destruction to have withstood the buffetting involved. This objection is probably not applicable in the case of the welded tuffs, for the vaporous cushion which is generally considered to surround the fragments of such material (see Oliver, 1954) would obviate the destruction of the corona envisaged by Walker. Furthermore, in a rock from Scafell Pike, which is one of the



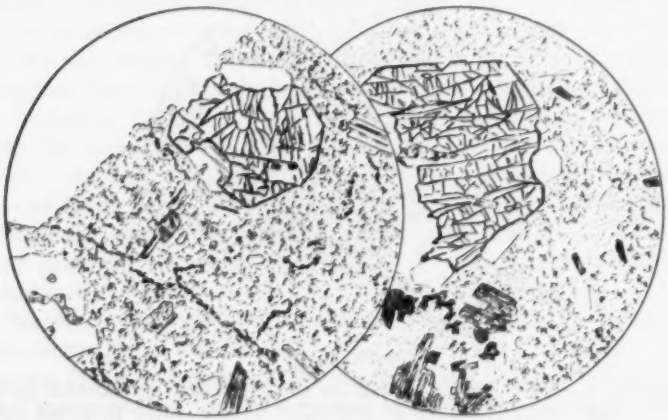
TEXT-FIG. 4.—Flow lines in rhyodacite swirling round idiomorphic garnet and feldspar; north of High Gait Crags. Plain polarized light. × 11.

two examples from normal tuffs, quoted by Walker, the feldspar crystals of the corona are tightly packed; and, in the opinion of the present writer, the garnet plus feldspar could quite conceivably have been ejected from a volcanic vent, and incorporated in a tuff deposit, without fracturing.

In Text-fig. 5, of garnetiferous biotite quartz-porphyry, from Scafell, are seen two large garnets with well formed crystal faces except where in contact with euhedral quartz. A similar garnet-quartz association is figured by Walker (1904, plate 13, 3), who ascribes the feature to corrosion of the garnet by the quartz. Green (1915), commenting on Walker's illustration, dissents from this view, maintaining that the quartz has interrupted the growth of the later-forming garnet. The present writer considers that the garnet and quartz, at least as shown in Text-fig. 5, have crystallized more or less simultaneously, for the euhedral outline of both the garnet and the quartz is interrupted.

There can be little doubt as to the magmatic origin of the quartz, and the above-described feature is strong evidence for the garnet's like genesis. In the same rock, and also in others, the prior crystallization of biotite, relative to garnet, is indicated by the inclusion of the former in the latter.

It is noticeable that, in some of the flow-banded garnetiferous rocks flow lines swirl round garnet phenocrysts (Slide No. 77085), and garnet with feldspar corona (see Text-fig. 4 and Slide No. 3835). The writer considers that this feature is strong evidence for crystallization of the garnet phenocrysts before solidification of the lava; though the possibility that the flow lines have swirled round a glomeroporphyritic feldspar cluster, and the garnet has been formed from part, or all, of



TEXT-FIG. 5.—Garnet phenocrysts associated with hypidiomorphic quartz, in biotite quartz-porphyry, Scafell. Note that completion of the idiomorphic outline of both garnet and quartz has been interrupted where in contact with each other. Plain polarized light. × 20 and × 14 (see illustration).

the feldspar and included iron ore, subsequent to consolidation, cannot be denied from a consideration of this feature alone.

A garnetiferous aplite dyke which is presumably related to the intrusion of the Eskdale–Wasdale Head granite, cuts hornfelsed andesite in Gable Beck. The garnets are spongy, with inclusions of the magmatic quartz and green biotite common throughout the rock.

The apparent instability of the garnets in the proximity of the Eskdale–Wasdale Head granite is suggested, for example, in a contact-altered rhyodacite from Peers Gill (Slide No. 77078), where what appear to have been idiomorphic garnets are now represented by aggregates of garnet, brown biotite, chlorite, epidote, iron ore and feldspar. Similarly, a strongly hornfelsed rock a few inches from the

Eskdale granite contact, half a mile north of Boot, Eskdale, contains small (up to 1 mm. diameter) garnets surrounded by a dense zone of fine-grained biotite. Dr. R. J. Firman (unpublished thesis, Durham University, 1953), however, suggests that the garnets are not necessarily unstable within the Eskdale granite aureole and that the biotite is a contact alteration product of earlier formed retrograde chlorite. Both interpretations imply that the garnets were present in the volcanics before the intrusion of the Eskdale granite.

Firman's conclusion is more easily reconciled with the presence of completely unaffected garnets, bounded by perfect crystal facets, in strongly metamorphosed rocks from Raven Crag and Illgill Head. Here there is another possibility, however, viz. that these garnets, which appear to be stable so close to the Eskdale granite (the Raven Crag rock is within a few inches of the intrusive rock), are true contact garnets. Walker (1904, pp. 102–103) describes what he considers to be garnets formed by contact action in ash xenoliths contained in intrusive quartz-porphyry, outcropping west of Stony Tarn, Eskdale, and in Peers Gill. The present writer has not seen any verification of this in rocks from the latter locality, but garnets in Walker's slice of the Stony Tarn xenolith (Slide No. 3887) have spongy peripheries which are freely penetrated by quartz similar to that in the recrystallized rock, and definitely have the appearance of metamorphic crystals.

On the north-east slopes of Base Brown, near Seathwaite, Borrowdale, garnets of apparent metamorphic origin are concentrated along the contact between porphyry and andesitic tuff. The garnets are contained in both rock types, and their formation would seem to have been facilitated by reciprocal movement of material across the contact.

Chemical and Physical Considerations

For all the "complete" garnet analyses shown in Table 1, the ratio $RO : R_2O_3 ; RO_2$ is as follows:

1. 3·17 : 1 : 3·00
2. 3·00 : 1 : 2·97
3. 2·93 : 1 : 2·91
4. 2·96 : 1 : 2·95
5. 3·03 : 1 : 2·94
6. 2·83 : 1 : 2·81
7. 2·96 : 1 : 2·77
8. 2·83 : 1 : 2·80

There is a tendency for the R_2O_3 to be in excess, which generally speaking, Fleischer (1937) maintains is due to oxidation of some of the FeO and the consequent recording of high Fe_2O_3; but the writer considers that such oxidation is unlikely to have taken place in the garnets concerned because the RO group is already slightly in excess

of RO_2. Some of the divergence from the ideal 3 : 1 : 3 ratio in garnet Nos. 3, 4, 5 and 6 may be explained on the assumption that a small amount of Al replaces Si to balance the inclusion of Ti^{4+} in the trivalent group. Titanium is not likely to be present as Ti^{3+} (Goldschmidt, 1954, p. 412) and Ti^{4+} (0·68 Å) cannot easily substitute for Si^{4+} (0·42 Å). In garnet No. 6, divergence might be due also to further substitution of Si by Al, and accompanying replacement of Fe^{2+} by Fe^{3+} (see Alderman, 1935), but it is more probable that experimental error is responsible for any remaining discrepancy in this garnet, and in others too. The general formula for the Lake District garnets may thus be written

$$(Ca\ Mg\ Fe''\ Mn)_3\ (Al\ Fe''\ Ti'')_2\ (SiAl)_3O_{12}$$

or $$(Ca\ Mg\ Fe''\ Mn)_3\ (Al\ Fe'')_2\ Si_3O_{12}.$$

Other components present in small amount are gallium, scandium, chromium and yttrium (see Table 2).

Ga^{3+} (0·62 Å) may be considered to substitute for the unvarying Al^{3+} (0·57 Å), as in other garnets (Jaffe, 1951, p. 146) and indeed, as in most other minerals. The chromium content in the Lake District garnets is small, and the variation probably not significant. Y^{3+} (1·06 Å), according to Jaffe (1951), is most abundant (up to ca. 20,000 ppm.) in spessartitic garnets, substituting for Mn (0·91 Å). That such replacement is possible is indicated by the subsequent experimental work of Yoder and Keith (1951) which shows the existence of complete solid solution between spessartite $Mn_3Al_2(SiO_4)_3$ and yttrogarnet $Y_3Al_2(AlO_4)_3$. It is noteworthy that garnet No. 8, with the highest manganese content, has also the greatest quantity of yttrium. Sc^{3+} (0·83 Å) is found to be a characteristic trace element in pyrope-rich garnets (Jaffe, 1951), substituting probably for Mg^{2+} (0·78 Å) or possibly for Fe^{2+} (0·83 Å). Among the Lake District garnets, variation in scandium content can definitely be correlated with variation in magnesium content.

Previous to the present work, only one complete Lake District garnet analysis has been published, viz. by Green (1915, p. 210). The rather high Fe_2O_3 (6·12%) of this analysis is suspect. Walker noted (1904, p. 101) that the Lake District garnets are "iron alumina garnets, with small quantities of calcium, magnesium, titanium, and manganese oxides, and therefore belong to the almandine type". Hadfield and Whiteside (1936, p. 58) record the manganese content of garnets from a variety of rock types in the Lake District; and the amount of manganese in four garnets from the Eskdale granite has been determined by Brammall and Bracewell (1936, p. 256).

Comparison of the composition of the garnets concerned with that of garnets from other rocks reveals that there is no significant compositional difference between the Lake District garnets and either

TABLE 1.—ANALYSES AND FORMULAE OF GARNETS

	1	2	3	4	5
SiO_2	37·32	36·96	36·73	37·02	36·59
Al_2O_3	20·89	20·65	20·21	20·86	21·02
TiO_2	tr.	–	0·28	0·28	0·08
Fe_2O_3	0·30	0·70	1·33	–	–
FeO	32·07	34·30	33·75	35·11	34·51
MnO	2·00	2·45	3·40	3·22	3·04
MgO	5·62	3·17	2·53	2·35	2·53
CaO	2·49	1·81	1·94	1·51	2·37
	100·69	100·04	100·17	100·35	100·14
	Molecules per cent.				
Almandine	67·27	75·24	73·44	79·00	76·43
Spessartite	4·22	5·36	7·50	7·27	6·85
Pyrope	20·97	12·46	9·84	9·37	10·03
Grossular	6·64	5·05	5·47	4·36	6·69
Andradite	0·90	1·89	3·75	–	–

	6	7	8	9	10
SiO_2	36·59	35·55	36·25	–	–
Al_2O_3	21·61	21·79	21·11	–	–
TiO_2	0·09	–	tr.	–	–
Fe_2O_3	0·57	–	1·42	–	–
FeO	33·78	33·46	31·65	33·16[1]	–
MnO	3·32	3·72	5·92	5·07	7·14
MgO	2·57	1·76	2·38	1·53[2]	–
CaO	1·90	4·06	1·63	–	–
	100·43	100·34	100·36		
	Molecules per cent.				
Almandine	75·08	73·50	69·01	76·73[2]	
Spessartite	7·51	8·20	12·99	11·59[2]	
Pyrope	10·22	6·94	9·23	6·45[2]	
Grossular	5·43	11·36	4·54	2·24[2]	
Andradite	1·76	–	4·23	2·86[2]	

FORMULAE ON BASIS OF 12 OXYGENS

		1	2	3	4	5	6	7	8
RO_2	Si	2·959	2·991	2·983	2·993	2·968	2·962	2·888	2·937
	Al	–	–	0·015	0·015	0·005	0·005	–	–
R_2O_3	Al	1·950	1·562	1·915	1·974	1·999	2·014	2·088	2·013
	Ti	–	–	0·015	0·015	0·005	0·005	–	–
	Fe^{III}	0·019	0·039	0·078	–	–	0·039	–	0·087
RO	Fe^{II}	2·112	2·312	2·286	2·367	2·330	2·277	2·268	2·140
	Mn	0·133	0·165	0·234	0·218	0·209	0·228	0·254	0·404
	Mg	0·666	0·384	0·307	0·286	0·306	0·311	0·215	0·292
	Ca	0·213	0·155	0·171	0·131	0·204	0·165	0·356	0·141
RO_2		2·959	2·991	2·998	3·008	2·973	2·967	2·888	2·937
R_2O_3		1·969	2·001	2·008	1·989	2·004	2·058	2·088	2·100
RO		3·124	3·016	2·998	3·002	3·049	2·981	3·093	2·977

1. Garnet from andesite (Spec. No. 76952), Stonethwaite, Borrowdale.
2. Garnet from andesitic tuff (Spec. No. 77038), Crinkle Crags.
3. Garnet from rhyodacite (Spec. Nos. 77085 and 77076), Lord's Rake.
4. Garnet from dacite (Spec. No. 77042), north-west of Mickledore.
5. Garnet from rhyodacitic tuff (writer's field Nos. 414 and 415), Green Gable.
6. Garnet from rhyodacitic tuff (e.g. Spec. Nos. 77028–77031), Sty Head.
7. Garnet from rhyodacitic tuff (Spec. No. 77138), north slopes Allen Crags.
8. Garnet from "quartz porphyrite" breccia (Spec. No. 77226), Ore Gap.
9. Garnet from biotic quartz porphyry (Spec. No. 77181), Cam Spout Crag.
10. Garnet from apilite (Spec. No. 77163), near Wasdale Head.

[1] Total Fe as FeO. [2] Calculated.

those from biotite schists (see Wright, 1938) or those from many contact and metasomatic rocks (Alderman, 1935; Folinsbee, 1941; Stewart, 1942; etc.); garnets from gneisses (e.g. Stewart, 1950) also may be similar to those of the Lake District. Heritsch (1927) groups the garnets from pegmatite, mica schist, granite vein, and granite vein in gneiss, with a compositional range not dissimilar from those shown in Table 1.

There would thus seem to be no reason, on the basis of major element composition, why the Lake District garnets are not of regional or contact metamorphic, or metasomatic, origin; though, in general, garnets which, under conditions of regional metamorphism, have been developed before the formation of biotite are likely to be more manganiferous than those concerned here (see Harker, 1932, p. 217). Metasomatic, or hydrothermal,[1] garnets also usually have fairly high manganese, as have, for example, those in vesicles of rhyolite from Colorado (Cross, 1886), and from Nevada (Pabst, 1938), with 28·48% and 11·96% respectively; or, alternatively, consist mainly of andradite, or grossular-andradite (e.g. Ohmori, 1941; Smellie, 1915). Williams

TABLE 2.—TRACE ELEMENT CONTENT (ppm)[2] OF LAKE DISTRICT GARNETS
Garnets numbered as in Table 1

	Cr	Sc	Y	Ga
Garnet No. 2	12	2000	2000	25
3	6	700	2000	25
4	—	750	2500	25
5	5	650	2500	25
6	5	420	2000	30
8	30	310	3000	20

(1922) records hydrothermal almandine from a rhyolite at Capel Curig, North Wales, but he gives no analysis or physical properties of the garnet.

In all the garnets analysed, the amount of yttrium is high, and comparable with that in many granitic and pegmatitic garnets (Jaffe, 1951, Table 2). Insofar as a metasomatic environment is not so different from a pegmatitic one, the yttrium content of the Lake District garnets seems not incompatible with a metasomatic origin, though in this connection it is noteworthy that Björlykke (1937, quoted by Jaffe, 1951, p. 144), in Norway, distinguishes metasomatic pegmatites from magmatic pegmatites by the fact that spessartitic garnets in the latter

[1] In this paper, the term *metasomatic* is used with reference to the action of late stage vapours and solutions emanating from a large intrusion (e.g. the Eskdale granite); the term *hydrothermal* is applied to late, or post volcanic activity.

[2] Trace elements were determined according to the method described by Nockolds and Allen (1953, pp. 105–106).

possess yttrium "in considerable amounts", whereas those of the former contain "no detectable amounts of Y elements". The high yttrium in the Lake District garnets conflicts with the possibility that they have been formed by regional metamorphism for Jaffe (1951, p. 153) states that yttrium is not a characteristic component of schist garnets. High scandium in the Lake District garnets (cf. Jaffe, 1951, Table 6) might be considered indicative of a metasomatic origin. Low chromium reflects, presumably, the relatively acid nature of the crystallizing environment, as compared, for example, with the 500 ppm. Cr^{3+} in an eclogitic garnet from Ballantrae (Dr. J. B. Allen, unpublished thesis, Cambridge University, 1953).

Table 1 shows that the garnets from the mineralogically more acid rocks contain, on the whole, more manganese and less magnesium than those from the rocks of more basic composition. The relationship is more clearly demonstrated in Table 3; and is reflected in Table 2 by the variation in scandium, substituting for magnesium, and perhaps in yttrium, substituting for manganese. It is reflected also in Table 4, where greater cell size means more abundant iron (relative to magne-

TABLE 3.—RELATIONSHIP BETWEEN MANGANESE-IRON AND IRON-MAGNESIUM RATIOS OF GARNETS AND THE CONTAINING ROCK TYPES

Rock type	*Composition of garnets* $\frac{MnO}{FeO + Fe_2O_3}$	$\frac{FeO + Fe_2O_3}{MgO}$
1. Andesite	·062	5·8
2. Andesitic tuff	·070	11·0
3. Rhyodacite	·097	13·9
4. Dacite	·092	14·9
5. Rhyodacitic tuff	·088	13·6
6. Rhyodacitic tuff	·097	13·4
7. Rhyodacitic tuff	·111	19·0
8. "Quartz porphyrite" breccia	·179	13·9
9. Biotite quartz porphyry	·153	21·7

TABLE 4.—RELATIONSHIP BETWEEN PHYSICAL PROPERTIES OF LAKE DISTRICT GARNETS AND THE CONTAINING ROCK TYPES

Rock type	*Physical properties of garnets* *Cell Dimensions* Å ± 0·002	*Refractive Index* ± 0·002	*Density* ± 0·05
1. Andesite	11·532	1·788—1·802	4·23
2. Andesitic tuff	11·541	1·813	4·22
3. Rhyodacite	11·542	1·815	4·23
4. Dacite	11·541	1·826	4·20
5. Rhyodacitic tuff	11·542	1·817	4·25
6. Rhyodacitic tuff	11·541	1·817	4·25
7. Rhyodacitic tuff	11·542	1·820	4·21
8. "Quartz porphyrite" breccia	11·548	1·820	4·20
9. Biotite quartz porphyry	11·549	1·818	4·24
10. Aplite	11·547	1·825	4·275

sium) and more manganese; variation in the Fe/Mg ratio is shown also (though not so clearly) by the change of refractive index.

Variation in the manganese content of other Lake District garnets (Hadfield and Whiteside, 1936, p. 58) does not fully substantiate the above relationship, and its validity must be accepted with reserve. The differences in composition of the garnets analysed by the writer are small, and well within the random variation of, for example, garnets in the Dartmoor granite (Brammall and Bracewell, 1936, p. 255). Correspondence between the composition of the Lake District garnets and that of the environment, as suggested, is to be expected in igneous rocks,[1] under equilibrium conditions, though also, perhaps, in low grade metamorphic rocks. It would not be expected in the case of garnets included as xenocrysts from a hypothetical basement, nor, probably, in the case of metasomatic or hydrothermal garnets. As igneous *phenocrysts*, or as crystal fragments in tuffs, the garnets would not be in complete equilibrium with the environment, and indeed, as igneous minerals, disequilibrium is indicated by the commonly associated feldspar corona. Under such conditions of incomplete igneous equilibrium, discrepancies, alluded to above, in the correlation between the composition of the garnets and of the containing rock are to be expected, though (on the assumption that the Lake District garnets are of igneous origin) without destroying completely the rough relationship as illustrated in Tables 2, 3 and 4.

Considered as a whole, the Lake District garnets seem further related to their environment in that their very presence or absence appears dependent on the composition of the containing rock. Walker (1904, p. 96) noticed that the composition of the garnetiferous "streaky" rocks ranges in silica percentage from 63 to 69. Garnet-bearing rocks, corresponding to this group, which have been analysed by the writer (Spec. Nos. 77042 and 77034) contain 62·66% and 67·02% silica respectively. The Falcon Crag andesites of Marr (1916), with 59% to 61% silica contain garnets, and it is noteworthy that the Eycott lavas, with 51% to 53% silica (Harker, 1891) are not garnetiferous. An analysis (quoted by Walker, 1904) of a quartz-garnet-mica-porphyrite from near Blea Crag, Langstrath, has 60·02% silica. The silica content of the Low Rigg and Threlkeld microgranites ranges (Hadfield and Whiteside, 1936) from 67·18% to 70·14%, though it is not known whether all the (four) rocks contain garnets. A garnetiferous biotite-quartz-porphyry, analysed by the writer, contains 68·50% silica.

The silica percentage of the above, which are all the analysed Lake

[1] Garnets from pyroxenite, gabbro, mangerite, and mangerite syenite, in Heidal, Norway, are considered by Gjelsvik (1947) to show a crystallization series with decreasing Mg and increasing Fe" in those from basic to acid rocks respectively.

District garnet-bearing rocks known to the writer, ranges from 59 to 70. It is noteworthy that elsewhere, similar rocks from which, in the molten state, almandine-rich garnets are considered to have crystallized, may be similarly limited in composition.[1]

Some idea of the physical conditions under which the Lake District garnets may have crystallized can be derived from artificial experiment. Schairer and Yagi (1952, p. 497) found that prolonged heating of garnet from Botallack, Cornwall, caused it to decompose at 900°C, and, in a hydrothermal environment, at a temperature of 500°C. Their conclusion from this, and other evidence, is that a mineral of comparable composition might be present in rock assemblages at temperatures somewhat below 900°C. The Botallack garnet is 91% almandine, 1·7% spessartite, 2·4% pyrope, 4·6% grossular. The stability range of the Lake District garnets would be at a higher temperature than that at which the Botallack garnet is stable because of a greater average pyrope content in those of the Lake District (see Ramberg, 1952, fig. 30). An also greater average spessartite content, however, has the effect of lowering the temperature at which the Lake District garnets would be stable (cf. Michel-Levy, 1951; Miyashiro, 1953). On balance, the average temperature of stability of the Lake District garnets is perhaps not greatly dissimilar from that of the Botallack garnet, and they may be considered, therefore, to have crystallized "at temperatures somewhat below 900°C".

Such a temperature, though ill-defined, is probably greater than that normally associated with a metasomatic or post-volcanic hydrothermal environment, but it is probably not significantly different from the temperature of an andesitic or dacitic magma.

Concerning the effect of pressure on the stability range of almandine-rich garnet, it should be noted that this appears to be considerable (see Harker, 1954, p. 458; and Yoder, 1955), though not, it is thought, so great as to invalidate any of the above considerations.

Conclusions

It is considered that the distribution of the Lake District garnets concerned precludes the possibility of all but a few having been formed as the result of contact metamorphism; and that a metamorphic para-

[1] Of the twenty-four analyses of the Dartmoor granite (Brammall and Harwood, 1932) one, with garnet, has 68·71 per cent. silica, and the silica content of nearly all the others (without garnet) is distinctly higher. In Victoria, Australia, the silica percentage of five garnetiferous dacites ranges from 65·80 to 67·85, and associated rhyolites, in which garnets are virtually absent, have 74·39 per cent. and 74·72 per cent. silica (Edwards, 1932). In New Zealand, however, garnets are reported (Cox, 1926; Speight, 1928) to be present in both pitchstone, with 69·54 per cent. silica, and rhyolite, with 75·68 per cent. silica.

genesis (either contact or regional) is unlikely also because there is no evidence that the containing rocks, in general, have been significantly affected by metamorphism. The possibility that the garnets have formed under hydrothermal or metasomatic conditions is also not favoured because temperatures normally prevailing in such an environment are thought to be substantially lower than the crystallization temperature of the garnets concerned.

There is, however, considerable petrographic evidence pointing to the presence of the garnets in the "Borrowdale" magma before its intrusion, extrusion, or ejection. For example:

1. The swirling, in lavas, of flow lines round the garnets.
2. The occurrence of lapilli or xenoliths of what appears to be originally garnetiferous Borrowdale volcanic material.
3. Many of the garnets in tuffs appear to be definite crystal fragments.
4. Apparent crystallization of garnet before, or together with, phenocrystic feldspar in both extrusive and intrusive rocks.
5. Apparent simultaneous crystallization of garnet and phenocrystic quartz in quartz-porphyry.

It is thought improbable that the garnets in the Borrowdale volcanics and associated rocks are xenocrysts from an almandine-rich "basement", because such an origin would result in a very much more random compositional distribution of the garnets than appears to be the case. Garnets in the microgranites of Threlkeld and Low Rigg are apparently xenocrystal, but these are probably derived from the Borrowdale volcanics (Hadfield and Whiteside, 1936, p. 59). One or two garnetiferous xenoliths, or fragments, in otherwise non-garnetiferous lava or tuff also are thought to have originated in earlier volcanic rocks.

That the garnets crystallized from the "Borrowdale" magma itself, therefore, seems likely. The suggestion that, in several rocks, plagioclase, similar to that present as normal phenocrysts, is replacing garnet implies that the latter were formed at a fairly early stage in the cooling history, though, at least in one rock, later than the biotite phenocrysts. It is not certain that garnets from the volcanic sequence and from the intrusive rocks belong to the same magma, though similar environments appear to have conditioned the crystallization in both cases.

Acknowledgments

Thanks are due to Professor C. E. Tilley for guidance throughout the work, to Dr. S. R. Nockolds and Mr. R. Allen for trace element analyses, and to Mr. K. Rickson for taking X-ray photographs.

REFERENCES

ALDERMAN, A. R., 1935. Almandine from Botallack, Cornwall. *Miner. Mag.*, xxiv, 42–48.

BRAMMALL, A., and S. BRACEWELL, 1933. Garnet in the Dartmoor Granite; its Petrogenetic Significance. *Nature*, cxxxi, 250.

—— and S. BRACEWELL, 1936. The Variability of Garnet in Granites. *Miner. Mag.*, xxiv, 254–256.

—— and H. S. HARWOOD, 1932. The Dartmoor Granites: Their Genetic Relationship. *Quart. Journ. Geol. Soc.*, lxxxviii, 171.

COX, P. T., 1926. Geology of the Rakaia Gorge District. *Trans. New Zealand Inst.*, lvi, 95–101.

CROSS, WHITMAN, 1886. On the Occurrence of Topaz and Garnet in Lithophyses of Rhyolite. *Amer. Journ. Sci.*, Ser. 2, xxxi, 432.

EDWARDS, A. B., 1932. The Geology and Petrology of the Black Spur Area (Healesville). *Proc. Roy. Soc. Victoria*, xliv, 49–76.

—— 1936. On the Occurrence of Almandine Garnets in some Devonian Igneous Rocks of Victoria. *Proc. Roy. Soc. Victoria*, xlix, pt. 1 (n.s.), 40.

FLEISCHER, M., 1937. The Relation between Chemical Composition and Physical Properties in the Garnet Group. *Amer. Min.*, xxii, 751–759.

FOLINSBEE, R. E., 1941. The Chemical Composition of Garnet associated with Cordierite. *Amer. Min.*, xxvi, 50–53.

GJELSVIK, TORE, 1947. Anorthosittkomplekset i Heidal. *Norsk. Geol. Tidsskrift*, xxvi, 54.

GOLDSCHMIDT, V. M., 1954. *Geochemistry*. Oxford.

GREEN, J. F. N., 1915. The Garnets and Streaky Rocks of the English Lake District. *Miner. Mag.*, xvii, 207–217.

HADFIELD, G. S. and WHITESIDE, H. C. M., 1936. The Borrowdale Volcanic Series of High Rigg and the Adjoining Low Rigg Microgranite. *Proc. Geol. Assoc.*, xlvii, 42–64.

HANCOX, E. C., 1934. The Haweswater Dolerite. *Proc. Liverpool Geol. Soc.*, xvi, 173–197.

HARKER, A., 1891. The Ancient Lavas of the Lake District. *The Naturalist*, 145–147.

—— 1902. Notes on the Igneous Rocks of the English Lake District. *Proc. Yorkshire Geol. Soc.*, 14.

—— 1932. *Metamorphism*. Methuen, London.

—— and J. E. MARR, 1893. Supplementary Notes on the Metamorphic Rocks around the Shap Granite. *Quart. Journ. Geol. Soc.* xlix, 359–371.

HARKER, R. I., 1954. Further data on the Petrology of the Pelitic Hornfelses of the Carn Chuinneag-Inchbae Region, Ross-shire, with Special Reference to the Status of Almandine. *Geol. Mag.*, xci, 445–462.

HARTLEY, J. J., 1932. The Volcanic and other Igneous Rocks of Great and Little Langdale, Westmorland. *Proc. Geol. Assoc.*, xliii, 32–69.

—— 1942. The Geology of Helvellyn and the Southern Part of Thirlmere. *Quart. Journ. Geol. Soc.*, xcvii, 129–162.

HERITSCH, F., 1927. Studien über den Chemismus der Granaten. *Neues Jahrb. für Min.*, usw., B.B. lv., 60–91.

HOLLINGSWORTH, S. E., 1937. Carrock Fell and Adjoining Areas. *Proc. Yorkshire Geol. Soc.*, xxiii, 208–218.

JAFFE, H. W., 1951. The Role of Yttrium and other Minor Elements in the Garnet Group. *Amer. Min.*, xxxvi, 133–135.

MARR, J. E., 1900. Notes on the Geology of the English Lake District. *Proc. Geol. Assoc.*, xvi, 449–483.

—— 1916. *The Geology of the Lake District.* Cambridge.

MICHEL-LEVY, M. C., 1951. Reproduction artificielle de Grenats ferro-manganesiferes; serie almandin-spessartine. C.R. Acad. Sci., Paris, ccxxxii, 1953–1954.

MIYASHIRO, A., 1953. Calcium-poor Garnet in Relation to Metamorphism. *Geochim. Cosmochim. Acta*, iv, 179–208.

NOCKOLDS, S. R. and ALLEN, R., 1953. The Geochemistry of some Igneous Rock Series. *Geochim. Cosmochim. Acta*, iv, 105–142.

OHMORI, K., 1941. Studies of Garnet from Suisyo-yama in the Hida Mountains. *Journ. Jap. Assoc. Min. Pet. Econ. Geol.*, xxv, 189–205.

OLIVER, R. L., 1954. Welded Tuffs in the Borrowdale Volcanic Series, English Lake District, with a Note on Similar Rocks in Wales. *Geol. Mag.*, xci, 473–483.

PABST, A., 1938. Garnets from Vesicles in Rhyolite near Ely, Nevada. *Amer. Min.*, xxiii, 101–103.

RAMBERG, H., 1952. *The Origin of Metamorphic and Metasomatic Rocks.* Chicago.

RASTALL, R. H., 1910. The Skiddaw Granite and its Metamorphism. *Quart. Journ. Geol. Soc.*, lxvi, 116–141.

—— and W. H. WILCOCKSON, 1915. The Accessory Minerals of the Granitic Rocks of the English Lake District. *Quart. Journ. Geol. Soc.*, lxxi, 592–622.

SCHAIRER, J. F., and K. YAGI, 1952. The system FeO–Al_2O_3–SiO_2. *Amer. Journ. Sci.*, Bowen Volume, 471–512.

SHAND, S. J., 1945. Coronas and Coronites. *Bull. Geol. Soc. Amer.*, lvi, 247–266.

SMELLIE, W. R., 1915. The Igneous Rocks of Butte. *Trans. Geol. Soc., Glasgow*, xv, 334–373.

SORBY, H. C., 1880. Slates of the English Lake District: part of Presidential Address. *Quart. Journ. Geol. Soc.*, xxxvi, Proceedings, 74–75.

SPEIGHT, R., 1928. The Geology of the Malvern Hills. *New Zealand Geol. Surv. Mem.*, no. 1, 14–16.

STEWART, F. H., 1942. Chemical Data on a silica-poor argillaceous hornfels and its constituent minerals. *Miner. Mag.*, xxvi, 260–266.

—— 1950. Note on Garnet Crystals from Cairnie, Aberdeenshire. *Miner. Mag.*, xxix, 252–253.

TROTTER, F. M., S. E. HOLLINGWORTH, T. EASTWOOD, and W. C. C. ROSE, 1937. *Sheet Mem. Geol. Surv. Great Britain.* Gosforth District.

WALKER, E. E., 1904. Notes on the garnet bearing and associated rocks of the Borrowdale Volcanic Series. *Quart. Journ. Geol. Soc.*, lx, 70–105.

WILLIAMS, H., 1922. The Igneous Rocks of the Capel Curig District (North Wales). *Proc. Liverpool Geol. Soc.*, xiii, 166–206.

WILLIAMSON, W. O., 1935. The composite gneiss and contaminated granodiorite of Glen Shee, Perthshire. *Quart. Journ. Geol. Soc.* xci, 393–394.

WRIGHT, W. I., 1938. The Composition and Occurrence of Garnets. *Amer. Min.*, xxiii, 436–449.

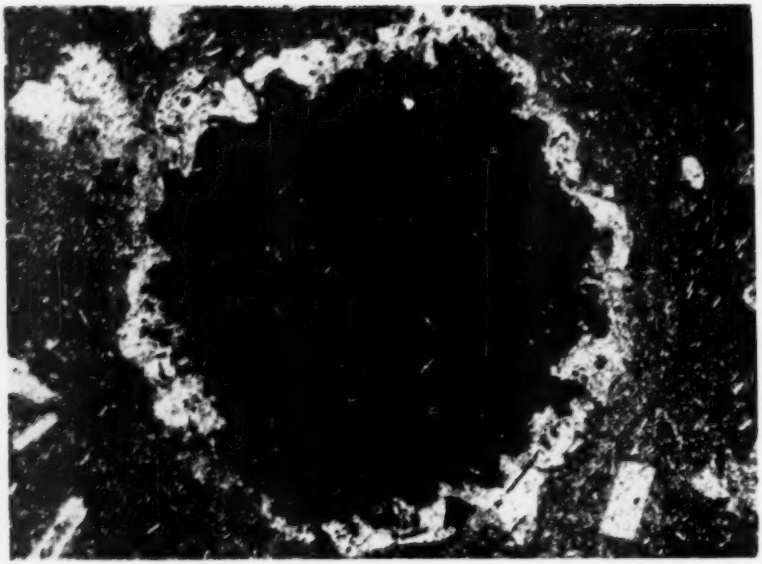


FIG. 1.

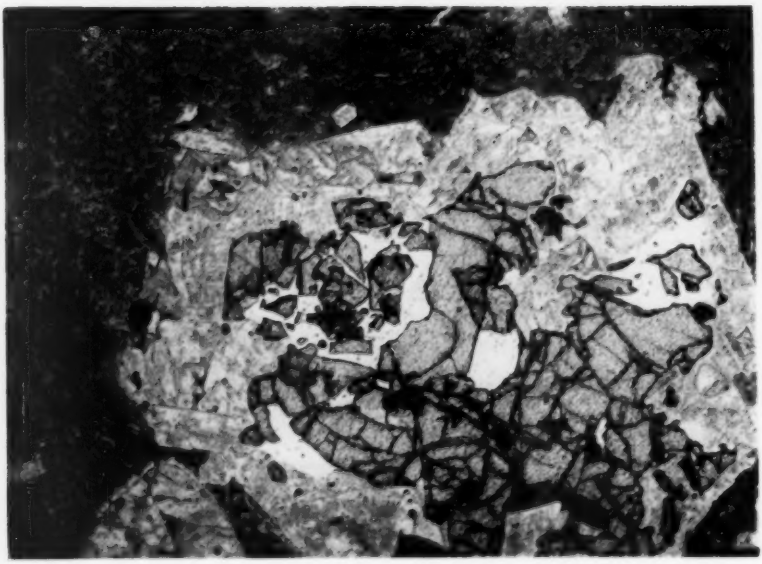


FIG. 2.

GARNETS IN BORROWDALE VOLCANIC ROCKS.

YODER, H. S., 1955. Almandite Garnet Stability Range. *Amer. Min.*, xl, 342 (abstract).

—— and M. L. KEITH, 1951. Complete substitution of aluminium for silicon: the system $3MnO.Al_2O_3.3SiO_2$–$3Y_2O_3.5Al_2O_3$. *Amer. Min.* xxxvi, 519.

c/o PHOTOGRAPHIC SURVEY CORPORATION, LTD.,
BOX 1339,
COLOMBO,
CEYLON.

EXPLANATION OF PLATE VI

FIG. 1.—Garnet with sericitized feldspar corona in rhyodacite, Great Gable. Crossed nicols. × 21.

FIG. 2.—Garnet associated with hypidiomorphic plagioclase (An_7) and minor iron ore; rhyodacitic welded tuff; Low Saddle, near Blea Tarn. Plain polarized light. × 28.

The Petrology of the Pre-Cambrian Rocks of the Southern Portion of Southampton Island

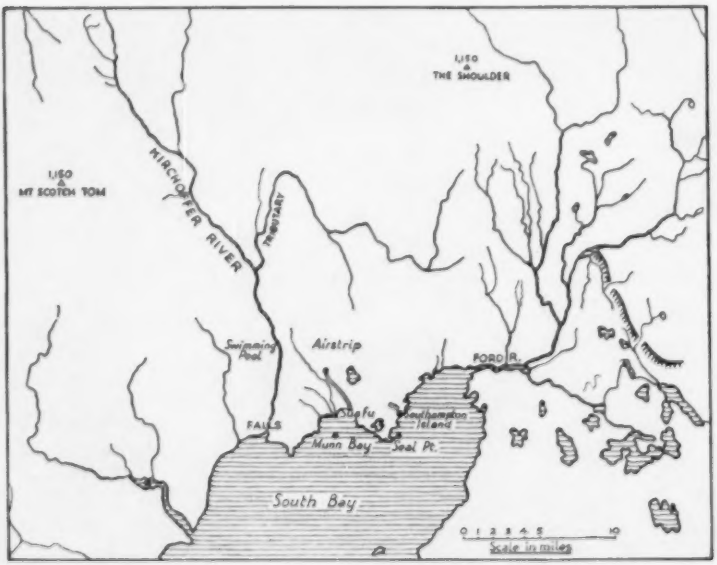
By John L. Daniels

Abstract

The pre-Cambrian rocks of the Southern portion of Southampton Island are composed of acid gneisses of very variable character containing a few, commonly zoned, xenoliths. The petrography of both is described; eight new analyses are given, and the probable origin of several of these xenoliths is suggested.

Introduction

THE pre-Cambrian rocks of Southampton Island, Hudson Bay, outcrop mainly in the north-east and east. Palaeozoic limestones cover the western and south-western regions, except near the mouth of the Kirchoffer River, which has uncovered the pre-Cambrian and produced a narrow gorge flanked by Palaeozoic rocks. The area investigated in the southern region of Southampton Island is approximately of 150 square miles, and bounded on the west and north by the Kirchoffer River and tributary (Text-fig. 1). The pre-Cambrian is composed of acid orthogneisses containing some basic inclusions. Much of the acid gneiss is finely banded and merges into smaller areas of coarser grained gneiss in which the banding is less well developed.



Text-fig. 1.—Sketch map of area of Southampton Island, Hudson Bay.

Ptygmatic folding is not common, but is sometimes developed where basic schlieren occur. Frequent pegmatite veins cut the gneiss, mainly following, but occasionally cross-cutting, the somewhat variable direction of tectonic strike, to follow well-defined joints. Basic inclusions, varying in size and degree of elongation, but generally less than 10 × 5 × 1 feet, often zoned, are not common, and their distribution is uneven; the largest concentration occurring in the Kirchoffer River region.

The Acid Gneisses

General Classification: Three varieties of acid gneiss are distinguished by the colour of the feldspar: grey, pink and pale olive-green gneiss. They occur either separately, or closely associated. The grey and pink gneisses predominate.

The Grey Gneisses.—Just west of the airstrip the rock is a banded grey biotite granodiorite-gneiss (Table 1, Anal. 1), with a few well defined pink bands up to half an inch wide. The latter are almost devoid of dark minerals in contrast with the colour index of 4.5 of the

Table 1

	1	*2*
SiO_2	71·66	62·03
TiO_2	·12	·72
Al_2O_3	16·74	21·41
Fe_2O_3	1·56	1·16
FeO	·24	·80
MgO	·09	1·65
CaO	2·34	4·06
Na_2O	4·71	3·51
K_2O	2·75	4·35
P_2O_5	·04	·49
MnO	·01	·05
H_2O+	·20	·42
H_2O-	·02	·04
	100·48	100·69

Norm.	*1*	*2*
Quartz	28·32	15·30
Orthoclase	16·68	26·13
Albite	39·82	29·34
Anorthite	11·68	16·68
Corundum	1·63	4·79
$MgSiO_3$	·20	4·10
Ilmenite	·30	1·37
Magnetite	·46	·46
Haematite	1·28	·96
Apatite	tr.	1·34

Mode.	*1*	*2*
Quartz	31·9	17·1
K-feldspar	11·5	16·0
Plagioclase	51·0	43·4
Biotite	3·8	3·9
Hornblende	–	15·5
Accessories	0·8	4·3

1. Biotite granodiorite-gneiss from west of airstrip.
2. Hornblende-biotite granodiorite-gneiss from junction of Kirchoffer River and tributary.

Analyst: J. L. Daniels.

grey bands. The quartz, carrying inclusions of potash feldspar and biotite, and the feldspars show rounded and interlocking grains and small areas of myrmekitic intergrowth are not uncommon. Potash feldspar occurs as microcline, microcline-perthite and antiperthitic inclusions in the plagioclase, a sodic oligoclase. Both feldspars carry inclusions of quartz and biotite. Slightly oriented, dark brown biotite occurs interstitially in the form of short laths. Inclusions are rare and only a few grains show alteration to chlorite and ore. Accessories include white mica associated mainly with the slightly altered biotite, and occasional iron ore and apatite.

North of Suafu, the grey hornblende-biotite granodiorite is also well banded, showing elongated quartz and conspicuous thin bands rich in mafics. Potash feldspar occurs as microcline and as antiperthitic inclusions in the plagioclase (An_{20}). In contrast with the biotite granodiorite-gneiss, the dark minerals, forming some five per cent. of the rock, are composed mainly of brownish green hornblende, partially replaced by chlorite, with less biotite and some iron ore. Occasional inclusions of labradorite occur in the hornblende. Accessory epidote and zircon are present. The biotite is red-brown in colour with γ 1·633, which is slightly lower than average for the acid gneisses.

A coarse grained biotite granite-gneiss, occurring eight miles up the Kirchoffer, is of interest since the potash feldspar is confined to antiperthitic inclusions, to a maximum of about twenty per cent. in the plagioclase (An_{10}). Dark red-brown biotite, partially chloritized, is the major accessory. Apatite, white mica and iron ore also occur in small quantities. A ferromagnesian-poor variety of grey gneiss from the Kirchoffer is very rich in quartz, which shows pronounced elongation and undulose extinction. Small areas have rounded sodic oligoclase and quartz enclosed in large, slightly perthitic potash feldspar.

The Pink Gneisses.—Pink, quartz-syenite-gneiss is also well developed near the biotite granodiorite-gneiss. It is coarse grained with irregular patches of dark minerals, but is not so well banded as the latter. The feldspar is mainly finely twinned, slightly antiperthitic, albite, with a smaller amount of potash feldspar. The latter occurs as orthoclase, microcline and, unlike the usual antiperthite of these gneisses, as small areas of intergrowth in the albite. Approximately equal proportions of potash and soda feldspars are present; the albite being in optical continuity with the enclosing plagioclase. Sericitization, often marked, has affected some of the feldspar. Of the remaining minerals, coarse grained reddish brown biotite is the most abundant. A few zircon inclusions are present, surrounded by pleochroic halos. Other accessories include white mica, apatite, haematite and pyrites.

A granitic variety of pink gneiss from west of the airstrip is similar to the quartz-syenite-gneiss in showing poorly developed banding and

irregular patches rich in biotite. The potash feldspar is microcline and the plagioclase is finely twinned slightly antiperthitic oligoclase. Quartz forms rounded grains, often as inclusions in the plagioclase. Chloritization of the biotite has occurred and is accompanied by numerous minute needles of rutile, mainly confined to the edges of the grains. Accessories include white mica, iron ore and small rounded zircons.

Similar types to this biotite granite-gneiss occur elsewhere, but differ mainly in the percentage of quartz present and the strength of the pleochroism and degree of alteration of the biotite. A well banded pink granitic gneiss near the Falls carries hornblende in small quantities as well as biotite. The amphibole is bluish-green and pseudomorphed, partially or wholly, by a mixture of calcite, chlorite, iron ore and serpentine. Biotite is closely associated with the hornblende, but is apparently more stable since it shows little sign of alteration.

Interbanded Grey and Pink Gneisses.—Often the grey and pink gneisses occur in thin alternating bands in approximately equal proportions. Here the grey gneiss is rich in dark minerals, while the pink gneiss is practically devoid of them. An occurrence of this type near Suafu carries well oriented biotite, often completely replaced by chlorite and granular sphene, as the only mafic mineral. Both potash feldspar and plagioclase (An_{10}) occur, but the ratio of the two varies from 1 : 3 to 4 : 1 in different parts of the specimen.

Ten miles N.N.E. of Suafu the gneiss is poorly foliated and the pink gneiss occurs as large patches in the grey gneiss.

Pale Olive Green Gneiss.—This type is not so frequently developed. Eight miles north of Seal Point a hornblende-biotite granodiorite-gneiss shows moderately well developed banding and thin planes of dark minerals. The potash feldspar is microperthitic orthoclase and the plagioclase (An_{15}) is strongly antiperthitic and carries small rounded quartz inclusions. The biotite forms short fresh laths in contrast to the associated pale bluish-green hornblende, which is often completely pseudomorphed by a mixture of chlorite, calcite, iron ore and brown serpentine. Accessories include iron ore, apatite, white mica and zircon.

Gneisses not included in the General Classification.—A coarse grained granodiorite-gneiss (Table 1, Anal. 2) from near the tributary of the Kirchoffer contains more hornblende and biotite than the normal acid gneiss and is relatively rich in apatite and iron ore. The quartz and feldspar form augen up to 2 cms. long, and there is a segregation of the light and dark minerals. The biotite, $\gamma = 1{\cdot}625$, is dark red brown and forms unaltered laths in close association with the dark green hornblende, $\gamma = 1{\cdot}677$, which is fractured and partially altered to chlorite and biotite. The apatite and ore occur mainly in the ferro-

magnesian-rich areas. The chemical and mineralogical analyses of this gneiss suggest that it has been highly contaminated, possibly by the incorporation of an amphibolite. Certain of the large amphibolite inclusions in the normal acid gneiss show a close mineralogical similarity to the ferromagnesian-rich areas of this grandiorite. The biotite γ is low compared with the biotite of the normal acid gneiss, but compares favourably with that for the biotites developed at the contact of amphibolite and acid gneiss. Compared with the biotite granodiorite-gneiss (Table 1, Anal. 1) it shows also, in general, an enrichment in those oxides concentrated at the junction of amphibolite and acid gneiss.

A meladiorite, from near Seal Point, and a hornblende-gabbro, from just south of Suafu, show no banding. They are not obviously related to the normal gneisses and their pre-Cambrian age is in doubt.

Basic Inclusions in the Acid Gneisses

Introduction.—Basic inclusions occur with moderate frequency in the Kirchoffer River region, especially in the Swimming Pool region, while fewer are present to the east. Their shape varies and depends on the degree of stretching which has taken place, and where extreme stretching has occurred an interbanded acid and basic rock results. Other examples show little or no elongation and their comparative, apparent, lack of plasticity during the time that the acid gneiss was foliated suggests that the inclusions are true xenoliths. Biotite, which is frequently developed around the inclusions, tails into the acid gneiss and accounts for at least a portion of the biotite there present. Their mineralogy is varied and commonly they are zoned, having an inner central pyroxene surrounded by a dark green hornblende, followed by a thin biotite-rich zone.

Petrology of a Zoned Xenolith from the Swimming Pool Region.

Four specimens from a large zoned xenolith, from the Swimming Pool region, Kirchoffer River, have been analysed (Table 2). The central, and outer pyroxene zones are dark, medium grained, show no conspicuous banding and are poor in light minerals. A certain amount of segregation of the minerals within the individual zones occurs, and this accounts, at least in part, for the variation in the mineralogy. In the central zone both bronzite and a diopsidic augite are present, the former predominating. Both pyroxenes show a rounded and corroded form, and transformation to amphibole is common. The bronzite (Fs_{25}) is pale pink and weakly pleochroic. Occasional lamellae of clinopyroxene, sometimes well developed, occur parallel to the optic axial plane, and trains of small inclusions are not infrequent. The amphibole is a weakly pleochroic tremolitic hornblende, and often

surrounds grains of both pyroxenes. Inclusions of quartz, iron ore and biotite may occur. The other essential constituent is a pale coloured magnesium rich biotite forming medium to large flakes, often with small oriented inclusions of iron ore. Usually the mineral shows bright bluish green patches peripherally and a birefringence similar to that of the pale biotite. Accessories include a small amount of untwinned interstitial plagioclase, a little quartz and iron ore which occurs sporadically as interstitial allotriomorphic crystals and as inclusions in the mafic minerals, as small rounded grains in the pyroxenes and angular grains in the amphibole. In the adjacent zone the pyroxenes, hornblende and biotite are deeper in colour and more pleochroic than in the central zone, while the light minerals are composed entirely of twinned plagioclase (An_{40}).

Surrounding the pyroxene zones is a narrow zone rich in dark green, strongly pleochroic and zoned hornblende, which is the only essential constituent. A small amount of iron ore and altered pyroxene are present, together with some tremolitic hornblende, chlorite and epidote as alteration products.

The outer zone is formed partially by transformation of the hornblende zone, in much of which extensive alteration occurs and has produced a somewhat patchy, dark yellowish-green, coarsely crystalline rock, containing pale green to colourless amphibole, epidote, chlorite, quartz and ilmenite, with lesser amounts of magnetite, haematite, apatite, leucoxene and potash feldspar. The pale coloured amphibole is a soda-tremolite, while in the most altered areas it is much paler in colour and is a weakly pleochroic tremolite. Pale amphibole occurs in four habits, which are related to different stages in the formation of the outer zone—as optically continuous crystals replacing the dark green hornblende of the hornblende zone, individual long, thin crystals associated with chlorite, large sheared crystals up to 2 cms. long closely associated with chlorite and as minute needles embedded in quartz. The chlorite is bright green and pleochroic, mainly associated with the pale amphibole, but occurring occasionally in small roughly circular areas and as vermicular aggregates in the quartz. Most of the epidote is colourless, but where closely associated with iron ore is pale lemon yellow and slightly pleochroic. Quartz is present interstitially, mainly associated with the epidote and often contains fine needles of pale amphibole and some chlorite. Ilmenite, often surrounded by yellow epidote, is practically confined to the epidote rich areas.

The mineralogical relationships between the outer composite zone and the inner dark green hornblende zone indicate that the former has been, in part, produced from the latter. The first stage of the alteration was the replacement of the dark green hornblende by a much paler soda-tremolite, ore, chlorite and epidote. This was followed by the

crystallization of chlorite and an independent soda-tremolite as along slender crystals. Where no dark green hornblende remains the amount of ore increases, and is accompanied by chloride, pale tremolitic amphibole, epidote and quartz in approximately equal amounts. A little potash feldspar but no plagioclase is present. The pale tremolitic amphibole, with chlorite developed along the cleavages, forms areas up to 2 cms. in length, while the quartz and epidote form small patches in which they occur with a few thin needles of amphilbole and a little potash feldspar, intergrown with the quartz.

TABLE 2

	3	*4*	*5*	*6*	*7*
SiO_2	49·14	47·16	45·30	43·34	46·49
TiO_2	·26	·27	1·01	·45	·48
Al_2O_3	11·27	14·17	13·57	14·43	11·62
Fe_2O_3	1·78	2·37	·85	9·10	3·38
FeO	6·93	8·90	10·50	6·42	9·18
MgO	17·00	14·44	12·70	7·74	13·86
CaO	6·71	5·56	10·80	13·69	9·45[1]
Na_2O	·64	·69	1·03	·17	1·69
K_2O	3·36	3·94	1·24	·20	1·62
MnO	·21	·26	·21	·33	·22
P_2O_5	·08	·08	·08	·21	·26
H_2O+	2·78	2·44	2·94	3·70	1·55
$H_2O—$	·07	·04	·02	·09	·10
	100·23	100·32	100·25	99·87	99·90

[1] Includes ·20 per cent. SrO.

Modes	*3*	*4*
Pyroxene	31·42	61·58
Amphibole	27·96	5·14
Biotite	39·49	26·46
Iron ore	·97	·13
Quartz	·18	–
Plagioclase		6·67

3. Central pyroxene zone of xenolith from Swimming Pool area.
4. Outer pyroxene zone from same xenolith.
5. Dark green hornblende zone from same xenolith.
6. Outer zone of same xenolith.
7. Hornblende zone from another xenolith from the Falls area.

Analyst: J. L. Daniels.

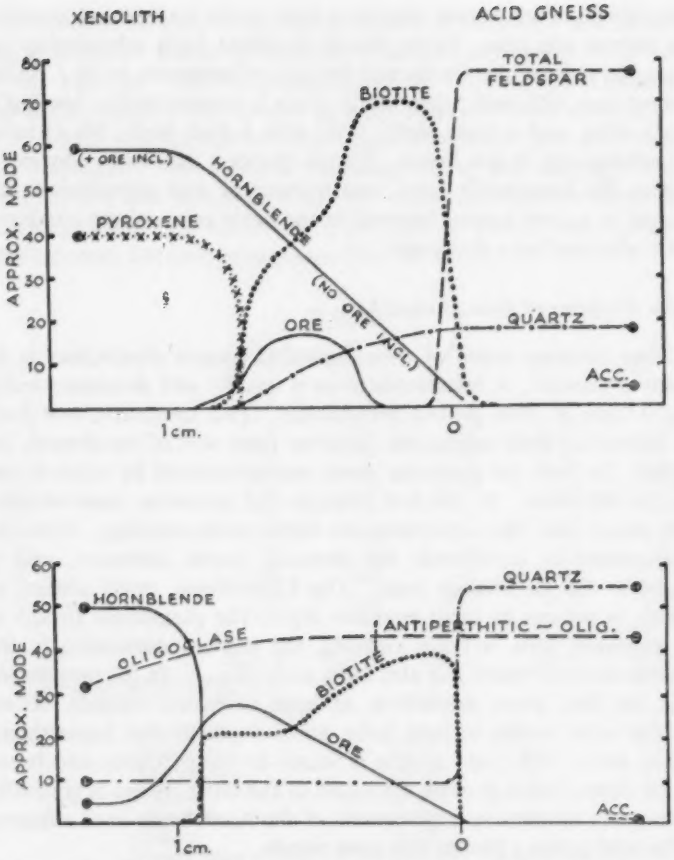
The chemical analyses (Table 2) show that from the core to the margin silica and magnesia decrease progressively, and alumina, lime and total iron increase. The state of oxidation of the iron is fairly constant in the pyroxene zones, falls in the hornblende zone and increases again in the outer zone. Total alkalis are fairly constant in the centre, decreasing towards the contact where the alkalis are very low. The relative amounts of soda and potash may be controlled by the magnesia and lime. Nockolds (1934) showed that magnesian rich

xenoliths absorbed potash relative to soda, while for lime rich xenoliths the reverse was true. There should therefore be a relationship between the ratio of the alkalis and the ratio of magnesia to lime. In the present case, although a low MgO : CaO is coupled with a low K_2O : Na_2O ratio, and a high MgO : CaO with a high K_2O : Na_2O ratio, the relationship is not linear. Titania shows a maximum concentration in the hornblende zone, and manganese and phosphorous are present in a little greater amount in the outer zone, where combined water also reaches a maximum.

Other Varieties of Zoned Xenoliths

Other common types of zoned xenolith contain plagioclase as an essential mineral. A hornblende zone is usually well developed and a biotite zone is often present peripherally. Two specimens, one from the Swimming Pool region and the other from west of the airstrip, are typical. In both the pyroxene zones are represented by relics in the hornblende zones. In the first example the pyroxene zone contains both ortho- and clino-pyroxene; the latter predominating. With the development of hornblende the diopsidic augite decreases, and is absent in the hornblende zone. The hypersthene, much altered to bastite, is present in small amounts only. The plagioclase (An_{35}) of the pyroxene zone is finely twinned, the amount decreasing in the hornblende zone where it is also more sodic (An_{25}). In the hornblende zone the dark green amphibole, as large subhedral crystals, occurs together with biotite in long laths, some much altered hypersthene, apatite and a little ore. Biotite is found in the pyroxene and hornblende zones, but it is more abundant in the latter, where it gradually increases in amount by replacement of the hornblende until adjacent to the acid gneiss a biotite rich zone occurs.

The second example shows several differences. One pyroxene only is present; a much altered diopsidic augite which is commonly replaced by hornblende. Iron ore, as large irregularly shaped grains, occurs in the pyroxene zone, and decreases with the development of the hornblende. The amphibole is dark greenish brown, strongly pleochroic, and accompanied by appreciable amounts of quartz and a little deep red biotite. The plagioclase is less abundant and more sodic in the hornblende zone. At the contact is a distinct zone rich in biotite and iron ore. The biotite is a deep red and distinguished from the biotite in the hornblende zone by the presence of pleochroic haloes surrounding zircon inclusions. Close to the contact the little plagioclase present is antiperthitic and has possibly been derived by mechanical mixing with the acid gneiss. The approximate mineral variation across the contact of two xenoliths is given in Text-fig. 2.



TEXT-FIG. 2.—Graphs showing approximate modal variation across contacts of two zoned xenoliths from Southampton Island.

Variation in Mineralogy of Centres of Xenoliths

The centres of the xenoliths show a considerable mineralogical variation and pyroxene, brown hornblende, green hornblende and garnet rich types may be distinguished. Those carrying appreciable amounts of hornblende are the most common. Garnet rich xenoliths are rare.

Pyroxene Rich Xenoliths.—Xenoliths having a similar mineralogical composition to the analysed biotite-hornblende-pyroxenite (Table 2, No. 3) are fairly common. An example from the Falls area contains colourless non-pleochroic orthopyroxene (Fs_{17}) poikilitically enclosing some of the magnesium-rich biotite. The hornblende is pale green

and present in small amounts occurring interstitially and as inclusions in the orthopyroxene. A little quartz is present. The development of the pale green hornblende may be observed in a similar xenolith in which it surrounds relics of a much altered pyroxene. It is commonly intergrown with quartz, a byproduct of the conversion of pyroxene to hornblende. As the hornblende is derived from pyroxene the modal percentage of the pale green hornblende may be used as an indication of the degree of transformation of the xenolith. It is also noted in this particular group of xenoliths that an increase in amount and colour of the hornblende is accompanied by a deepening in colour of the pyroxene and biotite. A small increase in iron ore is also observed. It is thus possible to trace the progressive transformation of this group of xenoliths. The first example contains the least hornblende, practically colourless pyroxene, pale biotite and negligible iron ore, and represents the least modified type, but since sudden changes in mineralogy are frequent it is not possible to estimate by extrapolation the composition of the original xenolith. Hornblende shows a decrease towards the least modified rock and it is reasonable to suggest that the earlier stage was hornblende free. The amount of biotite would be less, quartz may be present but iron ore absent, and it is therefore suggested that this group of xenoliths was derived from a rock consisting of colourless orthopyroxene near enstatite, possibly with some quartz, together with an unknown amount of biotite rich in the phlogopite molecule.

A pyroxene-rich xenolith from the Kirchoffer River region contains equigranular subhedral ortho- and clino-pyroxene and pale green hornblende in approximately equal amounts with iron ore occurring interstitially and as inclusions in the other minerals. A few rounded crystals of forsterite, altering to a yellow-brown serpentine, occur interstitially and as inclusions in the pyroxenes. The diopsidic augite contains numerous oriented needles and rounded grains of iron ore, and the strongly pleochroic hypersthene rounded inclusions of iron ore.

Brown Hornblende-Rich Xenoliths.—Xenoliths with golden brown to deep brown-green hornblende occur, in which the associated minerals are plagioclase, together with hypersthene or hypersthene and diopsidic augite. A little porphyroblastic garnet may be present. A fairly coarse grained xenolith from the Swimming Pool region contains golden brown hornblende, some with dark brown schiller inclusions. The hypersthene is strongly pleochroic, often closely associated with the hornblende, and forms rounded, sometimes elongated crystals, occasionally intergrown with the coarsely twinned plagioclase (An_{44}). Small rounded ore grains are frequently seen at the contact of the intergrowth of hypersthene and plagioclase with the hornblende. A little red-brown biotite is also present. These minerals develop mainly

perpendicular to (001) and are probably derived from the hornblende.

A xenolith from the Kirchoffer River region carries a few large, 3 cms., rather widely spaced garnets, enclosed in a matrix of dark greenish-brown hornblende, pleochroic hypersthene and some plagioclase (An_{45}). The garnets are almandine rich and surrounded by a narrow leucocratic zone up to ·5 cms. wide. Adjacent to the garnet the zone consists of elongated hypersthene and plagioclase, with their long axes at right angles to the garnet. This is followed outwards by a narrow, fairly well defined band of subhedral iron ore crystals. More remote, the hypersthene and plagioclase form less elongated crystals, similar to that assemblage resulting from the breakdown of brown hornblende. In contact with the enclosing amphibolite is a partial zone of hypersthene and a little plagioclase. A small amount of green hornblende and biotite is irregularly scattered throughout the zone. The composition of the plagioclase across the intergrowth varies from An_{75}, adjacent to the garnet to An_{62} near the band of iron ore grains. Beyond the ore band the composition varies irregularly between An_{60} and An_{50}. As garnets do not in general contain sodium, the presence of intermediate plagioclase shows that soda metasomatism or interaction of garnet and amphibolite has taken place.

Hypersthene is usually the only pyroxene present in the brown hornblende rich xenoliths, but occasionally hypersthene and a pale green diopsidic augite occur together. The plagioclase varies from sodic oligoclase to calcic adesine. It is possible that these xenoliths carrying brown hornblende have developed from metamorphosed basic igneous rocks. They closely resemble some reconstituted Adirondack gabbros (Buddington, 1952.) (See Table 3.)

Green Hornblende-Rich Xenoliths.—Dark green or brownish-green hornblende, often occurring as large subhedral crystals, may form up to 90 per cent. of these xenoliths. A few zoned hornblendes are present, but generally the colour is even throughout. Pale green diopsidic augite is usually present, sometimes accompanied by rounded altered grains of pleochroic hypersthene. Dark brown or red-brown biotite may occur in appreciable quantities generally increasing in amount towards the periphery. Plagioclase varies in amount and composition (An_{25-55}). Other accessories include iron ore, apatite and occasional brown-green tourmaline.

Green hornblende, especially the dark green to dark brownish-green varieties, is commonly developed in large amounts in the outer zones of most of the xenoliths, and those carrying this type of hornblende centrally would appear to represent enlarged hornblende zones (Table 2, Anals. 5, 7).

Garnet-Rich Xenoliths.—A typical garnet-rich xenolith from the

Kirchoffer River region contains pink almandine as subhedral crystals up to ·5 cms. in diameter forming approximately half of the rock. It contains many small inclusions of iron ore, biotite, feldspar and a few regularly arranged rounded grains of quartz. The remainder of the

TABLE 3.—COMPARISON OF CENTRE OF XENOLITH (8) FROM THE SWIMMING POOL AREA, WITH RECONSTITUTED ADIRONDACK GABBROS

	8	*A*	*B*	*C*	*D*
SiO_2	45·71	44·78	46·50	49·41	45·85
TiO_2	1·34	2·38	1·27	·91	2·03
Al_2O_3	14·41	17·64	16·86	16·61	18·44
Fe_2O_3	2·16	2·80	1·96	1·73	2·69
FeO	8·93	9·63	8·93	7·82	9·81
MgO	13·33	7·11	8·16	9·84	6·57
CaO	10·13	10·13	10·78	9·14	8·80
Na_2O	2·23	2·87	2·69	2·79	3·24
K_2O	·42	·64	·49	·63	·90
P_2O_5	·06	·42	·18	·12	·33
MnO	·05	·35	·15	·16	·27
H_2O+	1·29	1·28	1·30	·40	·81
H_2O-	·15	·13	·05	·05	·06
CO_2	n.d.	n.d.	·35	·13	n.d.
Cl	n.d.	n.d.	n.d.	n.d.	·35
	100·21	100·16	99·67	99·74	100·15
					100·07
					(less O for Cl)
Modes					
Plagioclase	48·0	30·0	29·6	41·9	46·5
Hypersthene	24·0	1·0	–	18·9	21·8
Augite	–	–	–	1·9	–
Hornblende	27·5	60·5	68·9	36·8	24·2
Biotite	·3	·8	·4	–	·2
Iron ore	·7	1·7	·2	·2	2·8
Sphene	–	–	–	·1	–
Apatite	–	1·0	·5	·2	·5
Garnet	–	5·0	–	–	4·0
Hornblende (γ)	1·671	1·689	1·684	1·680	1·696
Plagioclase	An_{65}	An_{47}	An_{54}	An_{54}	An_{44}

8. Centre of hornblendic xenolith from Swimming Pool area. Analyst: J. L. Daniels.

A. Almanditic amphibolite gneiss with porphyroblastic garnet. Stark Quad. Analyst: E. K. Oslund.

B. Amphibolite gneiss. Ogdensburg Quad. Analyst: S. S. Goldich.

C. Hornblende-hypersthene amphibolite gneiss from included angular fragment in hornblende granite. Malone Quad. Analyst: A. Willman.

D. Almanditic amphibolite gneiss with porphyroblastic garnet. Saranac Quad. Analyst: J. J. Engel.

rock consists of plagioclase and potash feldspar and red-brown biotite with inclusions of zircon. Some of the plagioclase and possibly most of the potash feldspar has entered the xenolith by way of small veins. These carry some large crystals of a coarse intergrowth of albite and potash feldspar in approximately equal amounts. The centre of one of

these shows a perthitic central portion grading outwards into antiperthite; the structure suggesting a replacement origin. These intergrowths resemble on a larger scale the potash feldspar-albite intergrowths of the quartz-syenite-gneiss previously described.

ACKNOWLEDGMENT

The specimens described in this paper were collected by Professor W. A. Deer, to whom the writer wishes to express his gratitude for the loan of the material and for assistance in preparing the paper.

REFERENCES

BUDDINGTON, A. F., 1952. Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic and quartz syenitic rocks. *Amer. Journ. Sci., Bowen Volume*, 37–84.

NOCKOLDS, S. R., 1934. The contaminated tonalite of Loch Awe, Argyll. *Quart. Journ. Geol. Soc.*, XC, 302–321.

DEPARTMENT OF GEOLOGY,
THE UNIVERSITY,
MANCHESTER.

The Pen-y-gader Dolerite and its Metasomatic Effects on the Llyn-y-gader Sediments

By R. G. Davies

Abstract

A petrochemical study of the Pen-y-Gader dolerite has been made. The intrusion produced a mild thermal metamorphism in the country sediments and then a late-stage metasomatism affecting the dolerite as well as producing spilosites and adinoles in the country rocks. The main metasomatism involved the introduction of sodium with small amounts of boron and fluorine into the sediments. The range of activity beneath the intrusion was governed by the porosity of the sediments affected, coarse-grained bands being followed for greater distances. The chemical and mineralogical variations within the dolerite have also been compared with those observed in certain of its ophitic neighbours.

Introduction

THE Pen-y-Gader Dolerite forms a conspicuous band in the upper part of the cwm which surrounds the moraine-dammed lake of Llyn-y-Gader in the county of Merioneth.

In his survey of the Cader Idris area, Sir Andrew Ramsay examined the intrusion and described it as a band of greenstone 250 feet thick, which alters slates above and below it into a hard porcellanite and is, therefore, not contemporaneous with the surrounding slates (Ramsay, 1866, 27).

The dolerite and the associated altered sediments were also referred to by A. H. Cox (1925, 560), and by A. H. Cox and A. K. Wells (1927, 290). They stated that the dolerite and the underlying granophyre had caused all the beds to be more or less spotted and contact altered, but that the porcellanous and adinole-like bands must, however, be due to original differences in composition and represent altered ashy material. It was considered that the interbanding of the adinole-like bands with ordinary slaty material is too intimate and too often repeated to be ascribed solely to contact action.

In view of the paucity of information regarding this well exposed sill and the spilositic and adinole-like bands in its neighbourhood, it was decided to make a detailed petrographic and chemical study of the assemblage concerned.

General Field and Stratigraphical Relationships

According to A. H. Cox (*loc. cit.*, 1925, 543), the stratigraphic succession in the country rocks is, in descending order :—

	Thickness in feet
Upper Acid Group . . .	900 to 1500
Llyn Cau Mudstone Group .	500
Upper Basic Volcanic Group .	400 to 500
Llyn-y-Gader Mudstone Group .	450 to 600
Oolitic Iron Ore Band . .	10 to 20

For a considerable part of its length, the outcrop of the Llyn-y-Gader Mudstone is split into a lower and an upper portion by the massive Llyn-y-Gader Ash. The lower mudstone is up to 150 feet thick. The upper mudstone varies considerably in thickness along the strike; east of Llyn Aran, its thickness rarely exceeds 30 feet but, between Twr Du and Cyfrwy, a maximum of about 400 feet may be

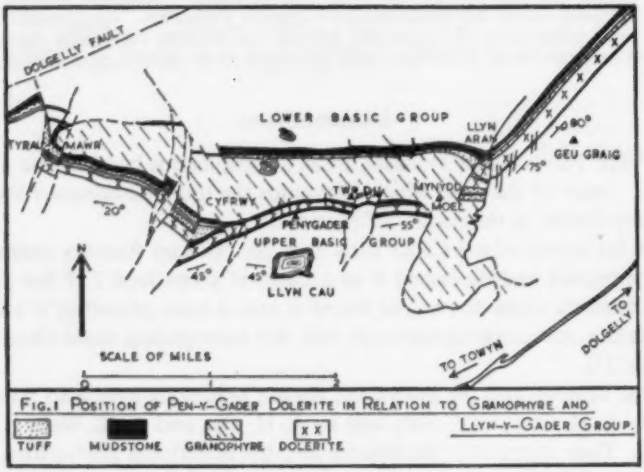


FIG. 1 POSITION OF PEN-Y-GADER DOLERITE IN RELATION TO GRANOPHYRE AND LLYN-Y-GADER GROUP.

reached. Near Tyrau Mawr, faulting occurs and the upper mudstones are considerably thinner on the west. It was into the upper mudstone band that the Pen-y-Gader dolerite was intruded.

The intrusion under discussion is a large sill, 300 feet thick above Llyn-y-Gader and as much as 600 feet to the north-east of Mynydd Moel. It is at least four miles long and probably considerably more, being traceable from the neighbourhood of Cross Foxes to the south-western slopes of Cyfrwy, at least. Text-fig. 1 is a sketch map showing the outcrop of the dolerite in relation to the other rocks and to the chief landmarks referred to in the paper.

The thinning of the upper Llyn-y-Gader mudstone to the east of Llyn Aran is considered by the writer to be an original feature of the sedimentation and not the result of assimilation of mudstone by the dolerite. Although there is some evidence of transgression by the

dolerite within the upper mudstones, it never encroaches into the sediments which lie below the Llyn-y-Gader ash. There is, however, another much thinner dolerite emplaced just below the ash, which separates it from the larger body. This rather thin sill is seen only in the area north of Geu Graig.

To the west of Llyn Aran, the problem becomes somewhat complicated owing to the presence of the great granophyre intrusion which makes up the bulk of Mynydd Moel and forms such an outstanding feature of the escarpment from Llyn Aran to Tyrau Mawr.

Relationships between the two intrusions and their country rock are best elaborated by means of Text-fig. 2. This diagram is an idealized section of the state of affairs probably existing when the Tal-y-Llyn Mudstone began to be laid down. A certain amount of evidence exists

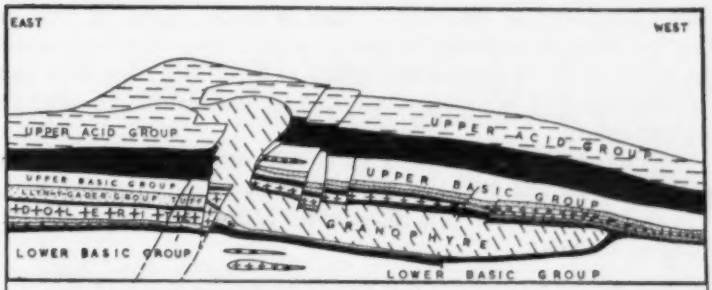


Fig. 2 Diagrammatic Section showing the Situation in Early Bala Times.

that some folding was in progress before as well as during and after the emplacement of the granophyre. This has been omitted from Text-fig. 2 in the interest of simplicity.

The available evidence suggests that the dolerite sill was intruded under quite a thin cover of rocks, consisting of part of the upper division of the Llyn-y-Gader Mudstone and the overlying Upper Basic Group, but before the Llyn Cau Mudstone was deposited. It was pointed out by A. H. Cox in 1925 (*loc. cit.*, 569) that not a single dolerite has been found above the Upper Basic rocks, a fact which appears to set an upward limit to the age of the basic intrusions. This opinion is reinforced by the close petrographic similarity which exists between the intrusive dolerites and the extrusive lavas of the Upper Basic Group, a resemblance which suggests derivation from a common magma. It may, therefore, be stated that, in all probability, the thickness of roof rocks did not exceed 600 feet and may have been rather less.

After the deposition of the Llyn Cau Mudstone, there followed the eruption of rhyolitic and andesitic materials to give rise to the Upper

Acid Group which is so well displayed in Craig Cau. Near or slightly after the end of this episode, the granophyre was emplaced.

If reference is now made to Text-fig. 2, it is seen that the outcrop of the dolerite, already broken by some faults, was radically interrupted near Mynydd Moel by the intrusion of the granophyre, that portion to the west being lifted and fractured with the roof rocks. Some folding was in progress at about the same time as the granophyre was emplaced, and this was made more intense by the much more powerful Post-Ordovician movements.

Examination of the dolerite outcrop has shown that between Mynydd Moel and Twr Du, the sill is close above the granophyre and is associated with tuff bands which occur locally in this part of the upper Llyn-y-Gader Mudstone. East of Llyn Aran, very little of the mudstone outcrop is present above or below the dolerite, so that a clear examination of the effects cannot be made. However, west of Twr Du there are sufficient thicknesses of mudstone above and below the intrusion for its metasomatic effects to be studied adequately and for these effects to be distinguished from the phenomena produced by the granophyre.

The rocks concerned are particularly well exposed in the cliffs north of Pen-y-Gader and it was in this locality that detailed observations were made and samples were collected for petrographic study and for chemical analysis.

The Rocks Exposed in the Cliffs North of Pen-y-Gader

A careful examination of the dolerite and of the associated rocks was first made in this well-exposed section. This was followed by the collection of samples for chemical analysis, in the following manner.

An outcrop or band of rock was selected and several large pieces of it were broken off so that clean, unweathered surfaces were exposed. These pieces were further broken down, clean, unweathered chips about half an inch long were collected from each and mixed together in a screw-capped bottle. It is considered that, when applied to medium and fine-grained rocks, this method is effective in producing a reasonably representative sample at a given point.

For every sample taken for chemical analysis, specimens were removed for the preparation of thin sections.

In addition to the samples taken from the dolerite in the neighbourhood of Pen-y-Gader, others were taken from its eastern portion and also from some ophitic dolerites which occur in the Mynydd Moel and Twr Du areas.

Prior to weighing for analysis the rock powders were dried at 110° C. The analyses were carried out by the methods described by Shapiro and Brannock (1952), using the Hilger UVISPEK instrument.

The results of the investigations will now be discussed according to whether they concern the dolerites, the roof sediments and the floor sediments of the Pen-y-Gader dolerite, in that order.

(*a*) *The Dolerites*

The Pen-y-Gader dolerite, which is between 250 and 300 feet thick at this point, shows little or no sign of chilling at the base and the lower half of the sill is coarser than that above. An increase in coarseness in the lower half in consequence of the gravity settling of crystals would not prevent the formation of a chilled margin at the base. In contrast, a distinct fine-grained zone may be observed immediately below the upper contact. This, which is of a pale-green colour, is probably a chilled margin somewhat contaminated by sediment from above. The rock from the central and lower portions of the sill tends to have a streaky brownish appearance. Jointing is marked and causes the formation of spindly columns which taper off at top and bottom.

In thin section, the rock from the centre of the sill is seen to be heavily saussuritized and consists of a granoblastic aggregate of secondary minerals. Epidote, which sometimes shows a pink pleochroism suggesting the presence of manganese, smaller amounts of zoisite and clinozoisite, ilmenite shreds, cloudy sphene granules and crystals occur with sheaf-like aggregates of a pale-green secondary amphibole.

These larger elements are set in a fine-grained mass of similar material together with irregular and patchy aggregates of quite anhedral quartz and albite, and of chlorite. Needles of a paler amphibole than that of the larger units cut across the albite-quartz and chlorite patches and form radial aggregates. Fibres of bright brown biotite are often associated with the amphibole.

The slides of the rock from the centre of the sill in that portion lying east of Llyn Aran show the same features.

In the fine-grained rock from the top of the sill, small needle-like crystals of albite and albite-quartz blebs are set in a fine grained matrix of chlorite and a granular titaniferous iron ore which is altering to granular sphene and leucoxene. Occasional small grains of epidote are seen.

Rock from near the base of the dolerite is seen in thin section to contain ragged laths of albite, fibrous and needle-like pale-green amphibole and biotite, chlorite, shreds of altering ilmenite, a little epidote and apatite together with patches of quartz and calcite.

The three dolerite types from the top, base and centre of the Pen-y-Gader sill can only be looked upon as products of autometasomatism.

In Table 1, analyses of the top, the centre and the base of the dolerite

(analyses numbered 1, 2 and 3) are given. Analysis number 4 is of dolerite from the centre of the sill east of Llyn Aran.

Consideration of these analyses allows the following generalizations to be made regarding the trends observed when taking the sill from top to bottom:

(i) Si and Al decrease regularly whereas Mg and Mn increase.
(ii) Ti is more concentrated in the base than in the centre and top.
(iii) Na and ferrous iron tend to be concentrated in the top and base.
(iv) P, K, Ca and ferric iron are concentrated in the centre.

It would seem that a relative decrease of Na, an oxidation of ferrous iron to ferric and a concentration of Ca in the centre are related to epidotization and amphibolitization. In contrast, a relative increase of

TABLE 1.—CHEMICAL ANALYSES OF DOLERITES

Analysis No.	1	2	3	4	5	6
SiO_2	57·9	55·1	52·4	53·4	49·2	48·7
TiO_2	2·29	2·29	2·9	2·18	1·40	1·41
Al_2O_3	15·4	14·6	14·3	15·9	14·4	15·0
Fe_2O_3	tr.	2·9	3·0	2·9	1·8	1·5
FeO	8·9	7·5	9·8	8·2	7·7	7·8
MnO	0·25	0·30	0·27	0·27	0·26	0·18
MgO	2·6	4·9	4·6	4·4	8·1	8·2
CaO	3·2	4·8	4·3	5·3	9·5	11·0
Na_2O	5·1	4·0	5·3	3·4	3·8	2·3
K_2O	0·05	0·25	0·23	0·80	0·04	0·08
P_2O_5	0·40	0·46	0·38	0·51	0·20	0·20
H_2O	3·5	3·0	3·5	2·9	2·7	2·8
Total	99·59	100·10	100·98	100·16	99·10	99·17

Na and ferrous iron in top and base may be correlated with albitization and chloritization, the former predominating in the base and the latter in the top.

Between Mynydd Moel and Twr Du, the rock from the Pen-y-Gader sill is often very coarse with a relict ophitic texture; the pyroxene has usually been largely replaced by a pale amphibole which often forms tiny blades cutting into the margins of the plagioclase. Samples may be found near Twr Du, in which appreciable amounts of pyroxene have survived. Such a rock, corresponding to Analysis No. 5, exhibits an ophitic relationship between albite-oligoclase and the clinopyroxene which is pink coloured. The plagioclase often appears cloudy as if partially altered and may have been more calcic when first formed. Small laths of plagioclase are sometimes poikilitically enclosed in the pyroxene. Appreciable amounts of secondary minerals occur interspersed between the ophitic groups. These include the pale amphibole,

zoisite, clinozoisite, chlorite and serpentine; leucoxene and sphene grow on ilmenite which may, from its ragged appearance, in part be secondary.

Rock from another neighbouring sill (Analysis No. 6), from the south-western slopes of Mynydd Moel, is very much less altered than the dolerite just described. Plagioclase concerned in the ordinary ophitic relationship with the pyroxene normally falls into the albite-oligoclase range. Poikilitic enclosure of feldspar in pyroxene is frequent and, in such cases, the plagioclase is usually andesine and sometimes labradorite in the fresher parts of the intrusion. Cloudiness is most frequently observed in plagioclase crystals which are not in contact with pyroxene; the bulk of the plagioclase does, however, appear quite fresh.

This dolerite is not devoid of alteration; it contains small blades of secondary tremolite growing on pyroxene and on plagioclase; zoisite and clinozoisite crystals occur here and there, patches of serpentine and anomalous-blue polarizing penninite are seen. In addition, granular sphene grows on ilmenite and a few groups of tiny red rutile crystals are visible.

The clinopyroxene once more possesses a faint pink tint and is sometimes slightly pleochroic. It is most probably a titaniferous variety of augite.

If the analyses for the poikilo-ophitic dolerite from Mynydd Moel (No. 6) and that for the centre of the Pen-y-Gader sill (No. 2) are recalculated in the manner of Barth, as ions per 160 ($O^{2-}+OH^{-}$) ions, the following results are obtained.

Ion	Si^{4+}	Al^{3+}	Na^{+}	K^{+}	Mg^{2+}	Ca^{2+}	Fe^{2+}	Fe^{3+}	Mn^{2+}	P^{5+}	Ti^{4+}	OH^{-}	O^{2-}
No. 2	49·4	15·4	6·9	0·3	6·6	4·6	7·3	2·0	0·23	0·35	1·6	9·0	151·0
No. 6	48·0	17·4	4·4	0·1	12·1	11·6	6·4	1·1	0·15	0·17	1·1	9·1	150·9

When the results are compared, it is seen that to obtain the Pen-y-Gader dolerite from the ophitic dolerite, for each unit cell, it would be necessary

(*a*) to add Si^{4+}, 1·4; Na^{+}, 2·5; K^{+}, 0·2; Fe^{2+}, 0·9; Fe^{3+}, 0·9; Mn^{2+}, 0·08; P^{5+}, 0·18; Ti^{4+}, 0·5 ions, and

(*b*) to remove Al^{3+}, 2·0; Mg^{2+}, 5·5; Ca^{2+}, 7·0 ions.

In addition, the evidence from the metasomatized sediments suggests that more sodium, a little boron and probably a little fluorine has been lost to the country rock. The difference in the figures for calcium and magnesium cannot be explained in terms of a metasomatic loss to the country rock since no calcite or dolomite rich veins occur.

(*b*) *The Roof Sediments*

The sediments which lie above the dolerite and which separate it from the Upper Basic Group, approach 100 feet in thickness and are lighter in colour than those occurring beneath the sill, often with a greenish tint. This indicates a low proportion of carbonaceous matter and may be due to the presence of material of volcanic origin, probably deposited quite rapidly. Metasomatic effects are mainly restricted to a fine white spotting which dies out about a foot from the contact. At distances greater than about four feet from the contact, little alteration, apart from a dark spotting which becomes more sparse as the distance is increased, is visible.

Thus, the action at the upper surface of the intrusion was restricted to the formation of a spilosite. The upper contact between the dolerite and the sediments is observable in the crest of the Llyn-y-Gader precipice a few yards north-east of Pen-y-Gader.

The spilosite was sampled just above the contact and samples of sediment were taken at two feet and about six feet above the dolerite. The spilosite has a pale green tint and is covered by small white spots. The spotting is seen under the microscope to be due to the formation of a patchwork of albite granules formed from the quartz grains in the original sediment and showing incipient twinning. Groups of these granules are partly enclosed in a meshwork of green chlorite, colourless sericite, granular sphene and leucoxene together with grains of magnetite and shreds of ilmenite. Occasional elongated crystals of pale-green tourmaline also occur. A textural grain, probably shadowing the original bedding, is seen in thin section as a chloritic streaking.

The second sediment contains no white spots. It is speckled with dark flecks which are seen in thin section to consist of titaniferous iron ore largely altered to leucoxene; chlorite is concentrated around the leucoxene granules to give compound flecks. The ground-mass consists of a fine-grained aggregate of chlorite, sericite and quartz; tiny granules of leucoxene occur throughout. In consequence of slight deformation, the flecks stand out as eye-like shapes bounded by shear lines which are often stained brown by limonite and which may contain carbonaceous matter.

In the third rock, the dark flecks, which are compounded of leucoxene, chlorite, sericite, quartz and finely granular albite, are sparsely distributed. The flecks, which are sometimes centred around clastic fragments of quartz and feldspar, appear to have grown at the expense of the ground-mass so displacing the surrounding micaceous minerals outward and concentrating them. Since this pushing was easier parallel to the bedding than across it, an augen structure resulted. The augen are embedded in a matrix of chlorite and sericite fibres which exhibit a distinct schistosity in a background of quartz. Interspersed through-

out the matrix are rather angular fragments of quartz, orthoclase and plagioclase up to 0·15 mm. long, about five to ten times the usual grain size in the matrix. Grains of sphene, leucoxene and altered iron ores with occasional crystals of zircon also occur.

Thus, in these roof sediments, three types of spots occur, albitic spots, chlorite-leucoxene flecks and sparsely occurring chlorite-leucoxene spots, in order of increasing distance from the contact.

Analyses of the three rock types which result are numbered 7, 8 and 9 respectively, and are shown in Table 2. They show clearly that the white spotting in the spilositic zone is due to the introduction of Na since the molecular ratio, Na/K, is 1·73. In normal sediments and in all the relatively unmetasomatized sediments analysed, the concentration of K is always much greater than that of Na, owing to ion exchange during sedimentation.

TABLE 2.—CHEMICAL ANALYSES OF ROOF SEDIMENTS

Analysis No.	7	8	9
Distance above contact	6 ins.	2 ft.	6 ft.
SiO_2 . .	50·4	54·6	71·3
TiO_2 . .	0·93	1·0	0·68
Al_2O_3 . .	23·1	22·5	13·8
Fe_2O_3 . .	1·2	1·7	1·4
FeO . .	6·6	6·1	2·6
MnO . .	0·24	0·17	0·13
MgO . .	3·0	2·1	1·0
CaO . .	1·8	0·83	0·80
Na_2O . .	4·4	0·22	0·64
K_2O . .	3·8	6·0	3·6
P_2O_5 . .	0·23	0·19	0·25
H_2O . .	4·2	3·8	2·6
Total . .	99·90	99·21	98·80

The incoming of Na has resulted in a displacement of K away from the spilositic zone and appears to have given rise to an increase in the amount of sericite just outside that zone and an increase in K recorded in the second analysis. The tournmaline present shows that the Na was accompanied by B and F.

Little can be deduced from the other figures obtained for the other major elements since the rocks appear to become more siliceous and less aluminous as the distance from the contact increases. This is probably the result of lithological variation during sedimentation.

The dark chlorite-leucoxene spots observed outside the spilosite zone are probably segregation spots, caused by the thermal phase of the contact action of the dolerite.

(*c*) *The Floor Sediments*

The base of the Pen-y-Gader dolerite is separated from the upper surface of the underlying granophyre by about 200 feet of the Llyn-y-Gader Mudstones. The acid intrusion did not cause extensive modifications in these sediments, effects being, mainly, thermal and mechanical rather than metasomatic and restricted in range. It is, in consequence, relatively easy to distinguish between the alterations produced by the two bodies.

The bulk of the sedimentary material lying between the granophyre and the dolerite is a dark grey mudstone which contains a thin but extensive sheet and also some small pods of spilitic dolerite. Adinoles accompany the dolerites. Also present are some impersistent bands of brownish weathering tuffaceous material.

For about twenty feet below the lower contact of the Pen-y-Gader dolerite, the sediments are strongly banded, intercalations of coarser material occurring in the normal mudstones. These bands are usually composed of normal sediment, although a few exhibit a brownish weathering suggesting the presence of ashy matter.

The zone in which altered sediments occur may be divided into two parts. In the first six feet or so below the dolerite contact, both fine-grained and coarse-grained materials are strongly adinolized, being baked and welded together to form a tough porcellanous band. The two types of bands can be distinguished, nevertheless, on freshly chipped surfaces.

At depths below the dolerite greater than about six feet, the adinolization of the fine-grained sediment falls off much more rapidly than is the case with the coarse-grained material. In consequence, as the depth increases, the coarse-grained bands become progressively conspicuous on account of their relatively high degree of alteration and resulting white weathering in contrast to the relatively lightly affected fine-grained mudstone.

In this outer zone, a striking effect is now visible. The incompetent mudstones, which have been affected only lightly by the adinolization, are cleaved as the result of stresses imposed after the metasomatic action. The comparatively competent, adinolized, coarse-grained bands are unaffected, apart from a slight cracking at right-angles to the bedding planes.

These adinoles are best examined in the upper portion of the buttress lying east of the Central Gully, approximately north-east of Pen-y-Gader. Two series of samples were collected to illustrate the variations occurring in the fine-grained and coarse-grained bands, respectively, with increasing distance beneath the dolerite. It was found that, in the very much indurated near-contact zone, it was not possible to

effect an adequate separation of the two types of bands by breaking up the rock with a hammer. Large specimens were removed, therefore, and the bands were sawn apart with a diamond impregnated rock cutting wheel.

(i) *Changes in fine-grained sediments*

The typical unaltered fine-grained sediment is a dark grey mudstone, sometimes finely banded, which, under the microscope, is seen to consist of a finely fibrous sericite and chlorite matrix in which are embedded occasional irregular granules of quartz, leucoxene and larger fragments of micaceous minerals. The banding is due to the concentration of coarser siliceous fragments in layers. Some of the chlorite is penninite. Streaks of magnetite occur here and there.

Few changes in the fine-grained sediments are noted, apart from an upward increase in the development of crystals of sericite and chlorite in the matrix until, at a point about seven feet below the contact, the edge of the inner zone is reached where both fine-grained and coarse-grained bands are heavily affected. At this point, the rocks seem to be cut by veinlets of albite which break across the fine-grained bands and also run along the bedding in the coarse-grained bands. Blebs of albite occur here and there in the fine-grained material but the bulk of the ground mass seems relatively unaffected. Occasional cavities, containing albite, quartz, sphene and limonite, occur as do small crystals of zircon.

From this point on, the amount of alteration of the ground-mass increases progressively; crystallization proceeds and a new texture develops. Under low power, blebs, patches and rope-like aggregates of green chlorite seem to be interspersed with a leucocratic matrix. Here and there, are a few blades of sericite but the fibrous sericite-chlorite intergrowths of the outer zone are absent.

Under high power, the leucocratic portion is seen to consist of a granular mosaic of albite, the chlorite and sericite now forming granular and feathery patches rather than fibrous intergrowths. Here and there, patches and blebs of granular sphene appear. The larger quartz grains have their margins more or less albitized, grading into the granular albite. In addition, well shaped, elongated crystals of tourmaline appear which vary in their individual pleochroism as follows, pale green to colourless, yellowish brown to pale yellow, yellowish brown to blue green.[1] Also present are some tiny needles of dark red to brownish red rutile which occurs associated with sphene and ilmenite.

[1] Agrell (1939, p. 315) had previously reported dravite-uvite tourmalines in the adinoles of Dinas Head in Cornwall but described them as being practically colourless.

Some very thin, slightly coarser, bands in the fine-grained sediments contain quartz which has been albitized, also fragments of plagioclase with albite apparently welded on to them, tourmaline and brightly polarizing hydro-mica which is probably damourite since it forms fan-like shapes.

(ii) *Changes in coarse-grained sediments*

Microscopic evidence shows that the larger, coarse-grained sedimentary bands contain irregularly shaped fragments of quartz and feldspar which show little or no sign of rounding. The feldspar fragments consist of sodic plagioclase and occasionally orthoclase. These larger grains are embedded in a rather dark, brownish matrix of chlorite, sericite and carbonaceous matter. The brown colour is due, largely, to limonitic staining. Dark streaks in the matrix and lighter streams of sericite fibres wave about to give a curious contorted structure, curling around the coarser grains. This would seem to be the result of the application of shearing stress to a band in which the coarser grains tended to remain rigid while the more plastic matrix was deformed around them.

Patches of granular sphene and leucoxene, about equal in size to the quartz and feldspar grains, occur generally. Rather rare fragments of apatite, zircon and a fragment of colourless, detrital, garnet are also seen.

The first visible effects of albitization of the coarse bands are noticed at about 20 feet below the contact, small pools of albitic material appearing here and there in small cavities. These effects increase rapidly two or three feet nearer the dolerite, quartz grains become noticeably patchy and some develop incipient twinning which indicates conversion to albite. Here and there, rather well-formed albite crystals, sometimes simply twinned and occasionally with window-pane twinning, are seen. These appear to have grown in place.

At the same time, a distortion occurs in the matrix and occasional needles of tourmaline appear in association with albite. Carbonaceous matter becomes more diffuse while the leucoxene aggregates become more crystalline and give rise to red rutile. In addition, crystals of a colourless garnet are seen. These contain carbonaceous inclusions. Occasional patches containing carbonaceous dust suggest relicts after garnet or even aluminosilicates produced by the pre-metasomatic thermal effect of the dolerite, but since dispersed during the metasomatism.

As the contact is approached, recrystallization of the micaceous minerals in the ground-mass increases, penninitic chlorite appearing in large patches while a granular intergrowth of albite is seen in the ground mass. Albitization of the larger quartz grains becomes more

marked. As the general fabric of the rock is little disturbed, many of these effects are not very noticeable under low power, but become obvious at high magnification.

The effects are most marked along the coarsest zones in the coarsest bands, which appear to have acted as channels for the movement of the metasomatizing substances.

About six feet beneath the contact, a further increase in intensity of the alteration is noted. The tourmaline minerals become rather common, although they are still of small size; the leucoxene becomes

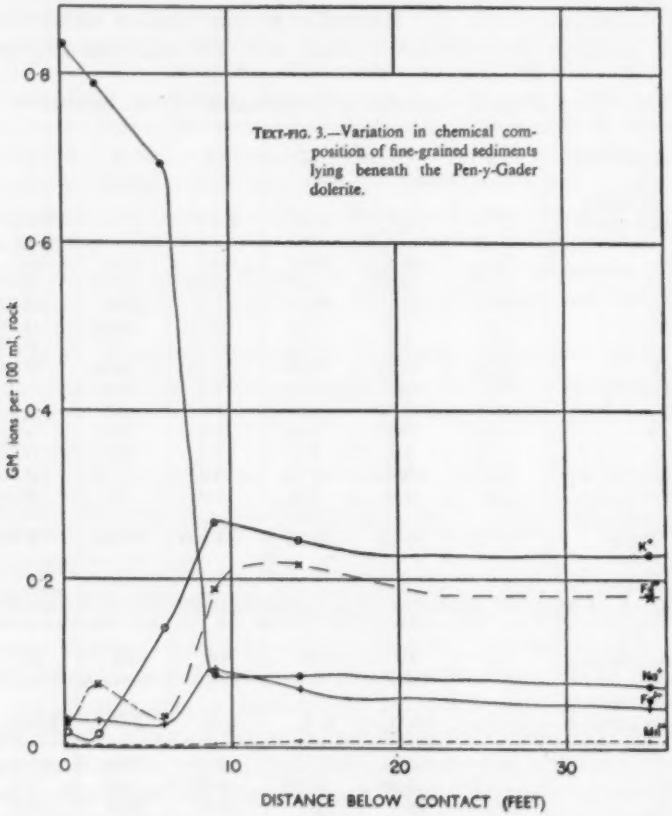
TABLE 3.—CHEMICAL ANALYSES OF FINE-GRAINED FLOOR SEDIMENTS

Analysis No.	10	11	12	13	14	15
Distance below contact	35 ft.	14 ft.	9 ft.	6 ft.	2 ft.	Cont.
SiO_2	62·3	58·1	56·1	60·5	61·4	64·7
TiO_2	0·77	0·86	0·97	0·94	0·77	0·77
Al_2O_3	17·5	20·0	21·0	21·2	18·8	18·3
Fe_2O_3	1·4	1·9	2·6	0·76	0·90	0·86
FeO	4·6	5·5	4·9	0·91	1·8	0·64
MnO	0·26	0·21	0·14	0·04	0·06	0·05
MgO	1·5	1·8	1·8	1·4	2·2	1·2
CaO	0·73	0·74	0·70	1·0	1·3	1·1
Na_2O	0·82	0·93	0·93	7·8	9·4	9·8
K_2O	3·9	4·1	4·5	2·4	0·21	0·33
P_2O_5	0·15	0·26	0·25	0·47	0·51	0·20
H_2O	3·8	4·4	3·2	1·9	1·3	0·75
Total	97·73	98·80	97·09	99·32	99·05	98·70

TABLE 4.—CHEMICAL ANALYSES OF COARSE-GRAINED FLOOR SEDIMENTS

Analysis No.	16	17	18	19	20	21
Distance below contact	22 ft.	16 ft.	8 ft.	6 ft.	2 ft.	Cont.
SiO_2	59·5	62·3	73·1	67·3	59·8	57·6
TiO_2	1·03	0·48	0·78	0·63	1·4	1·8
Al_2O_3	19·3	18·0	12·7	16·8	20·4	20·1
Fe_2O_3	1·5	1·9	0·89	0·38	0·92	0·87
FeO	5·3	3·3	1·9	0·16	1·6	3·3
MnO	0·20	0·14	0·06	0·02	0·07	0·15
MgO	2·5	1·1	0·78	0·25	2·2	2·4
CaO	tr.	0·66	0·80	0·91	1·2	2·2
Na_2O	0·85	5·0	5·9	10·8	8·3	8·8
K_2O	4·0	2·2	0·34	0·27	1·3	0·37
P_2O_5	0·37	0·25	0·42	0·28	0·63	0·59
H_2O	3·9	2·9	2·8	1·3	2·1	2·3
Total	98·45	98·23	100·47	99·10	99·92	100·48

replaced by fresh granules of sphene. Albitization of the coarse-grains is extensive and obvious. Veinlets of albite often cut across the finer bands from one coarse-grained band to another, the channels of rapid albitization being the coarser bands, the veinlets which join them probably following transverse fractures which existed prior to the metasomatic action.

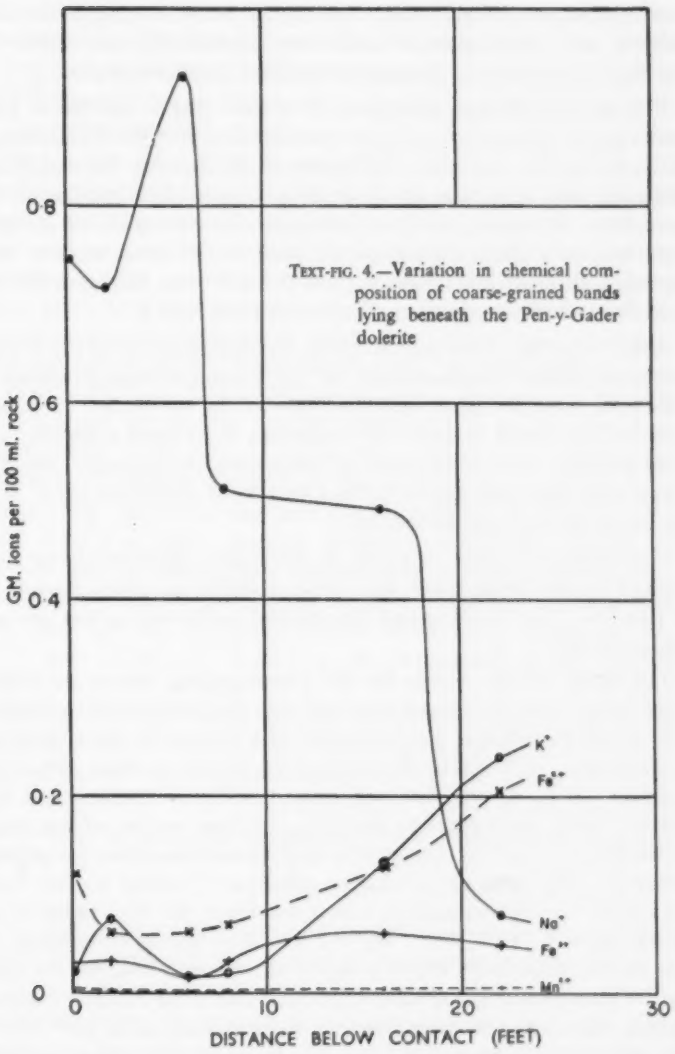


TEXT-FIG. 3.—Variation in chemical composition of fine-grained sediments lying beneath the Pen-y-Gader dolerite.

In so far as this inner zone is concerned, the intense metasomatism appears to have dispersed, completely, minerals such as garnet or aluminosilicates, which may have been formed earlier by thermal heating by the dolerite.

(iii) *The chemical effects of the metasomatism on the sediments*

The analytical results obtained on the two series, of fine-grained and coarse-grained bands, are presented in Tables 3 and 4, respectively.



TEXT-FIG. 4.—Variation in chemical composition of coarse-grained bands lying beneath the Pen-y-Gader dolerite

The depths below the contact, from which the samples were collected, are given in the tables but, owing to the steepness and roughness of the surface on which the transverses were made, the longer distances should be regarded as being rather approximate.

The chemical results have been plotted as graphs, in which distance below the contact is plotted against the number of gm. ions of a given

ionic species per 100 ml. rock. Text-figs. 3 and 4 are graphs for fine-grained and coarse-grained sediments respectively, and show the significant variations in the concentration of the elements.

For the fine-grained sediments, it is seen that :—(*a*) Na is concentrated for about six feet below the contact as is P, (*b*) the behaviour of K, Fe^{2+}, Mn and Fe^{3+} is antipathetic to that for Na which has displaced these ions from the inner zone so as to show maxima in the outer zone. However, insufficient analyses were carried out on samples from the outer zone to establish the positions of these maxima with accuracy, although the results suggest that Fe^{2+} was displaced further than Fe^{3+} which was, in turn, displaced further than K.

Apart from the above points, which are considered to be the important ones, further variations in Si, Al, Mg, Ca and Ti concentrations, of rather an irregular kind, may be observed in the table. It would, however, be unsafe to draw any inferences from them since they are most probably due to variations in the original sedimentary material. There does, however, appear to be a significant concentration of Si in the few inches nearest the contact.

Carbonaceous matter originally in the highly adinolized inner zone appears to have been driven out, most probably as carbon dioxide or as CO_3 ion. The unadinolized fine-grained sediments further out are still quite dark.

The trends of the curves for the coarse-grained bands are rather more complicated than those observed with the fine-grained sediments. This is, most probably, a consequence of a more diversified lithology in the former. As a result, the observed variations are more difficult to interpret. It is, nevertheless, still clear that Na is concentrated this time in a zone about eighteen feet wide, the inner six feet of this being particularly rich in Na. Ca shows a smooth decrease from the contact outwards. The other curves show a minimum at about six feet from the contact which corresponds with a maximum for Na. Outside the six feet point K, Fe^{2+}, Fe^{3+}, Mg and Mn show curves antipathetic to that for Na while Fe^{3+} shows a significant increase towards the contact. This suggests that a wave of sodium and some calcium metasomatism caused displacement away from the contact of K, Fe^{2+}, Fe^{3+}, Mg and Mn while some Fe^{3+} probably followed the sodium and calcium into the inner zone. In this case, only Fe^{3+} shows a maximum in the outer zone, the other displaced elements increasing progressively until the coarse banding peters out below. This is a consequence of the greater original porosity of the coarse sediments, the voids being filled rather than the original material being replaced, the outer fine-grained mudstones acting as a screen. The presence of tourmaline iu the coarse-grained and the fine-grained bands of the inner zone and in

the coarse-grained bands for a considerably greater distance from the contact shows that B and F were also introduced.

The variations of Si and Al are antipathetic and the maximum for Si at 8 feet merely means that there was a peak in the deposition of silica in the original coarse sediment.

In analysis number 21, representing a relatively unmetasomatized coarse-grained band, the amount of K greatly outweighs that of Na despite the fragments of plagioclase seen in thin section. The ion-exchange reactions which normally replace Na by K when a sediment is formed must have been oper[illegible] when this band was formed, especially with regard to its matrix. It would seem, therefore, that the coarse-grained bands were not rich in Na prior to the metasomatism and contrary to the opinions of Cox and Wells (1927, 290), the porcellanous and adinole-like bands, which have been shown to be rich in sodium, are not due to original differences in composition but to metasomatic additions, a consequence of original differences in porosity. Furthermore, most of the original material contained in them is regarded as having been normal sediment rather than altered ash. Coarse-grained, relatively unsorted, sediments must be more porous than the fine-grained end-products of sorting which form the mudstones. The metasomatizing substances, therefore, moved rapidly into and through the coarse-grained sedimentary bands and along transverse cracks and breaks in the fine-grained bands separating them.

The movement through the main body of the fine-grained sediment must have been a relatively slow matter and this explains the restriction of the intense metasomatic alteration of the mudstones to the inner zone some six feet or so from the contact. Alteration in this zone would be assisted by the higher temperature which would obtain there.

Discussion

In view of the results obtained on the Pen-y-Gader exposures, it is necessary to comment on some of the findings of earlier writers.

H. Dewey (1915, 71–74) attempted to relate the formation of adinole and spilosite to the degree of oxidation of the iron in the dolerite producing the metasomatism. He suggested that only intrusions with ratios of Fe_2O_3 to FeO greater than 1 to 3 gave rise to adinoles at contacts with slates. Dewey also believed that the state of oxidation of the iron in the country rock controlled the ease of adinolization; purple and red slates rich in Fe_2O_3 were considered to yield spotted slates, green slates developed spots and poor adinoles, while black slates, poor in Fe_2O_3, were markedly adinolized and did not develop spots.

S. O. Agrell (1939, 335) discussed Dewey's observations in the light of his own work in Cornwall and concluded that, contrary to Dewey's views, red and purple slates were sometimes adinolized in thin bands close to dolerite contacts, but Agrell agreed that richness in ferric iron in the red slates tended to inhibit reaction with metasomatizing substances and suggested that black slates contained iron in the ferrous condition, mainly in the chlorite, and therefore would react more readily. He considered, however, that this did not explain why pale-green slates, which he considered to be still richer in ferrous iron, were observed to be unreactive in the St. Mabyn Syncline. In consequence, Agrell was led to suggest that the grain size of the original sediment was important since the slightly adinolized red and green slates from the core of the syncline were much coarser in grain than the heavily adinolized black slates on its flanks. It may be inferred from this that he considered fine-grained sediments to be more readily affected than coarse-grained ones.

At Dinas Head, Agrell observed that on approaching the albite dolerite one passed through the sequence—unaltered slates, thermally spotted slates, partly metasomatized spilosites and adinoles. He considered that the adinolization had been a gentle replacement, taking place at constant volume since fine, as well as large scale bedding, pseudomorphs of andalusite and even casts of fossils were preserved undisturbed in the adinoles.

On the basis of chemical analyses and petrographic studies, he noted a similarity between adinoles and quartz keratophyres, concluding that adinoles were produced by addition of SiO_2, Na_2O, a little B_2O_3 and perhaps FeO to the slates. (The present work suggests that SiO_2 was of only slight importance at Pen-y-Gader.)

At Dinas Head, the adinoles and igneous rock were associated with ankerite and calcite. Agrell considered that the carbonate was derived in part from the intrusion and in part from the sediments which are known to contain calcerous bands.

The great bulk of the adinole at Dinas Head was correlated with the bulkiness of the intrusion supplying the metasomatizing fluids. These fluids albitized, carbonated and chloritized the dolerites and were the same as those which adinolized the country rock.

In the case of the Pen-y-Gader dolerite, the ratio of Fe_2O_3 to FeO is never more than about 1 to 2·6 while Dewey's graphs suggest 1 to 3 as the minimum ratio at which adinoles are formed.[1] The ophitic dolerites from the Twr Du and Mynydd Moel areas, which do not give rise to extensive adinoles, have Fe_2O_3 to FeO ratios of 1 : 4·4 and 1 : 5·3 respectively. In principle, therefore, it is possible to agree with Dewey that the lower the Fe_2O_3/FeO ratio, the lower the tendency

to form adinoles. However, higher Fe_2O_3/FeO ratios must be looked upon as the consequence of the presence in the igneous body of metasomatizing fluids which autometasomatize the body as well as adinolizing the country rock; they are not the cause of the activity. This view is reinforced by observations in the adinolized rocks below the Pen-y-Gader sill where there appears to have been some oxidation of ferrous iron to ferric during the metasomatism.

Beneath the dolerite, the least altered rocks have ratios of Fe_2O_3/FeO of 1 : 3·38 for the dark fine-grained mudstones, and 1 : 3·65 for the coarser bands. Above the intrusion, the pale greenish sediment gives a figure of 1 : 1·86. It is true to say that the upper pale greenish sediment was less affected by metasomatism than the lower, dark mudstones with lighter coarse bands but only because smaller quantities of metasomatising substances were released above the intrusion than below it.

Furthermore, Agrell's comment that pale green sediment contains a higher proportion of ferrous to ferric iron than does black mudstone does not apply here since the dark colour in the sediments is due to the presence of carbonaceous matter and not necessarily related to the amount of chlorite present. Greenish slates merely contain less carbonaceous matter and may or may not contain more chlorite or ferrous iron. No red slates occur on Cader Idris and no comment on them can be made.

The results on the Pen-y-Gader exposures show that the intensity and range of adinolization depend upon

(*a*) The concentration of adinolizing substances in the igneous material intruded.

(*b*) The mode of consolidation and emplacement of the intrusion.

(*c*) The grain-size distribution, and hence the porosity of the country rock, i.e. the presence in the country rock of channels which allow metasomatizing substances to move.

ACKNOWLEDGMENTS

The writer wishes to express his gratitude to Professor H. H. Read, Professor D. Williams and to Dr. W. S. Pitcher for the use of facilities for making the chemical analyses at the Imperial College of Science and Technology and to Mr. E. L. P. Mercy for checking two of the analyses. He also wishes to thank Professor Alan Wood and his colleagues at University College of Wales, Aberystwyth, for their constant encouragement and lively discussion.

[1] Agrell has erroneously stated this as 3 : 1.

LIST OF REFERENCES

AGRELL, S. O., 1939. The Adinoles of Dinas Head, Cornwall. *Miner. Mag.*, XXV, 305–337.

COX, A. H., 1925. The Geology of the Cader Idris Range. *Quart. Journ. Geol. Soc.*, lxxxi, 539–592.

COX, A. H., and A. K. WELLS, 1927. The Geology of the Dolgelly District, Merionethshire. *Proc. Geol. Assoc.*, XXXVIII, 265–318.

DEWEY, H., 1915. On spilosites and adinoles from north Cornwall. *Trans. Roy. Geol. Soc. Cornwall*, XV, 71–84.

RAMSAY, A. C., 1866. Geology of North Wales. *Mem. Geol. Surv.*, III, 27.

SHAPIRO, L., and W. W. BRANNOCK, 1952. Rapid Analysis of Silicate Rocks. *U.S. Geol. Surv. Circular*, 165.

DEPARTMENT OF GEOLOGY,
UNIVERSITY COLLEGE OF WALES,
ABERYSTWYTH.

Neoglyphioceras cf. *spirale* (Phillips) from Ingleborough

By William Hopkins

Abstract

The occurrence of a goniatite horizon in the Yoredale Series exposed on Ingleborough can now be recorded. The goniatite, *Neoglyphioceras* cf. *spirale* (Phillips) was found in shales underlying a limestone which may probably be the Five Yard.

DURING the course of a Durham University students' geological field week held in the Austwick area in the Easter vacation of 1954, an interesting discovery of a solid goniatite in the Yoredale Series exposed on Ingleborough was made by Mr. R. J. Kenna. In 1955 another excursion covered the same ground and a fragment of a second goniatite was obtained by Mr. E. S. Holmes from the same exposure in which the solid specimen was found. This occurrence of goniatites appears to be worthy of mention not only because of the rarity of goniatites in the Yoredale Series but also, because as far as I am aware, no goniatites have previously been recorded from Ingleborough.

The exposure (National Grid reference 746753 O.S. Popular One-inch Sheet 90) consists of shales clearly visible in the left bank of Mere Gill, Humphry Bottom, where the gill flows over the low lying ground below the prominent sandstone scarp underlying the Main Limestone of the Geological Survey on the north face of Ingleborough. The shales outcrop at approximately 1,630 ft. O.D. and are about 910 yards south-east of Mere Gill Hole.

There are two exposures of shale only a few yards apart, and it was from the lower one that the goniatites were obtained. The shales are dark, highly pyritized, and nodular in part, with numerous fossil brachiopods and mollusca. They occur beneath a richly fossiliferous shaly limestone about 15 ft. thick which is well exposed in the gill. The upper surface of this limestone is about 30 ft. below a spring shown near the 1,750 ft. contour on the 6 in. map, Yorkshire (West Riding) Sheet XCVI S.E. It is the first limestone exposed in Mere Gill below the Main Limestone and the prominent sandstone scarp of Ingleborough. It appears to be the Impure *Productus* Limestone of Phillips (McKenny Hughes, 1908, pl. xxix), which in the Ingleborough Memoir is regarded as the probable equivalent of the Five Yard Limestone of Alston Moor (Dakyns and others, 1890, p. 19), and also the thin limestone 8–10 feet thick recorded as the ?Five Yard in a recent guide to the geology of the Ingleborough district (Dunham and others, 1953, p. 98).

It is hoped that the new goniatite horizon will prove to extend over a wider area and be of assistance in solving the far from settled problem

of the identities of the limestones succeeding the Great Scar Limestone on the slopes of Ingleborough. The solid specimen was sent to Dr. C. J. Stubblefield for identification, who handed it to Dr. W. H. C. Ramsbottom. Dr. Ramsbottom reported as follows:

"The goniatite shows part of a suture line and a constriction. The ornament consists of moderately closely set spiral striae of the type which it would be unusual to find outside strata of P_2 age. The nearest described species is *Neoglyphioceras spirale* (Phillips) as revised by Bisat (1955), but it differs from that species in having fewer constrictions. There are about 24 spirals as against 25–30 in *spirale*. The name finally suggested is *Neoglyphioceras* cf. *spirale*. The horizon is probably low P_2."

The specimen is now housed in the Geological Survey Museum (GSM 86248). Unfortunately the second specimen was too broken for identification.

The precise stratigraphical position of this newly recorded goniatite horizon on Ingleborough cannot as yet be defined. All that can be said at present is that it occurs in shales underlying a limestone which may probably be the Five Yard. It is significant, however, that in Teesdale, the related low P_2 form *Goniatites* cf. *granosus* has been found in shales overlying the Scar Limestone (Rayner, 1953, p. 286). This limestone is the first limestone below the Five Yard in Teesdale.

I wish to express my sincere thanks to Dr. W. H. C. Ramsbottom for his kindness in identifying the specimen sent to him, to my colleagues for their co operation in the field, and to the students of both parties who searched enthusiastically for further specimens.

REFERENCES

DAKYNS, J. R., TIDDEMAN, R. H., GUNN, W., and STRAHAN, A., 1890. The Geology of the country around Ingleborough, etc. *Mem. Geol. Surv.*

HUGHES, MCKENNY T., 1908. Ingleborough, Part VI. The Carboniferous Rocks. *Proc. Yorks. Geol. Soc.*, xvi, 253–320.

RAYNER, D. H., 1953. The Lower Carboniferous Rocks in the north of England. *Proc. Yorks. Geol. Soc.*, xxviii, 231–315.

DUNHAM, K. C., HEMINGWAY, J. E., VERSEY, H. C., and WILCOCKSON, W. H., 1953. A Guide to the Geology of the district round Ingleborough *Proc. Yorks. Geol. Soc.*, xxix, 77–115.

BISAT, W. S., 1955. On *Neoglyphioceras spirale* (Phill.) and allied species. Publ. Ass. Étud. Paléont., xxi, 15–18.

GEOLOGY DEPARTMENT,
UNIVERSITY SCIENCE LABORATORIES,
DURHAM.

Fausto de Elhuyar (1755–1833), A Spanish Mining Geologist

By Joan M. Eyles

Abstract

Elhuyar, born in Spain in 1755, received a thorough training in mining geology at several of the leading European mining schools. He was appointed to an important post in New Spain (Mexico), where he arrived in 1788. There he devoted himself to reorganizing the administration of the mining industry and then to founding a School of Mines in Mexico City. This was opened in 1792, and in 1811 moved into the magnificent new building known as El Palacio de Minería, which now houses the Engineering School of the University. When an independent government was set up in Mexico in 1821, Elhuyar returned to Spain, where he continued to work for the government as a mining consultant. He prepared a report on the Rio Tinto mines and was responsible for the planning of the School of Mining Engineering in Madrid.

In the summer of 1956 geologists from all over the world will be travelling to Mexico to take part in the Twentieth International Geological Congress. It is therefore of especial interest to recall that over a hundred and sixty years ago, in 1788, a Spanish mining geologist, Don Fausto de Elhuyar y de Zubice, set off from Cadiz in the frigate *Venus*, bound for Vera Cruz and accompanied by his German bride and a small party of German mineralogists and master miners. Elhuyar was on his way to take up his new appointment as Director-General of the Mining Guild of New Spain, and only a few years after his arrival in Mexico was responsible for the opening of a School of Mines, the first technical college of the New World. As 11th October, 1955, was the bi-centenary of his birth, it seems worth relating something of his life and work, particularly as he has received very little attention in British works of reference.

Don Fausto was born at Logroño, not far from San Sebastian, and received his education at first near his home and later, from 1770–76, in Paris. When only twenty-two he was chosen to be the first professor of mineralogy in a college newly established at Vergara, near Bilbao, by the Sociedad Bascongada de Amigos del Pais, a Basque society for the promotion of learning. This society, founded in 1764, had opened the new college in 1777, and on the scientific staff were two Frenchmen who later became very well known ; one was J. L. Proust, who in 1797 first stated the Law of Constant Proportions, and the other was P. F. Chabaneau, later distinguished for his researches into the metallurgy of platinum.

The young Elhuyar had little or no knowledge of the subject he was to teach, and was sent by the Society to prepare himself for his post at the mining school at Freyberg, in Saxony. This academy was already

beginning to gain a European reputation through the teaching of the celebrated geologist, A. G. Werner. Don Fausto was accompanied by his elder brother Don Juan José, who had been specially commissioned by Charles III, King of Spain, to study metallurgy. The brothers arrived at Freyberg in 1778 and spent three years there, attending the various courses and visiting many mines and metallurgical centres, not only in Saxony but also in Austria and Hungary. Next they proceeded to Sweden, where Don Fausto spent six months studying chemistry at Uppsala under Tobern Bergman, who was widely known for his researches into mineral chemistry. In 1782 Fausto returned to Spain, by then, no doubt, a master of the latest techniques in chemistry and mineralogy, and well grounded in mining engineering and geology. At the end of the year he took up his post at Vergara, but combined research work with his teaching.

The first results of this research were published in the *Extractos de las Juntas de la Real Sociedad Bascongada* in 1783. This was an account by the Elhuyar brothers of the classic experiments in which they proved the identity of the acids obtained from the minerals scheelite and wolframite and, by reducing the acid obtained from the latter mineral, isolated a new metal. For this metal, now called tungsten, they proposed the name " wolfran ". The use of the international symbol W for tungsten is a reminder that the metal was first obtained from wolframite.

Although the Elhuyars' account appeared in an obscure and now extremely rare publication, it did not escape notice, and French and English translations appeared in 1785, and a German one soon after. The work was particularly welcomed by the Swedish chemists Bergman and Scheele, who had themselves isolated tungstic acid two years before, but had been unsuccessful in obtaining the metal. It is more than likely that the problem had been suggested to Don Fausto as a piece of research when he studied in Sweden.

Don Fausto published other papers in the *Extractos*, but in September, 1785, finding himself with very few pupils, he resigned his chair at Vergara and went to Madrid with his brother. Soon after the latter was appointed Director of Mines in New Granada (Colombia) ; but Fausto did not obtain an immediate appointment and returned to Vergara for the winter. Here, according to a detailed letter written to his brother in the following March, he seems to have collaborated with Chabaneau in the latter's attempts to render platinum malleable, the experiments meeting with some success. The process, however, was kept secret, and Chabaneau moved to Madrid, where he continued his work in a magnificent laboratory provided by the king.

In the same letter Fausto mentions he was about to go to Vienna, on the instructions of the king, to undertake some further study. The object

of this visit was to investigate a new metallurgical process which had been introduced by the distinguished Austrian mineralogist, Baron Ignaz von Born. Whilst there, in July, 1786, Fausto was notified that he had been nominated by the king as the new Director of the executive body that controlled the mining industry in New Spain (Mexico). Charles III had received advices from Mexico informing him that there was no local candidate suitable for this important post and requesting that someone with high qualifications be sent out from Spain. In order to fit himself still further for this post Fausto spent two more years in studying mining and metallurgy at the Mining Academy at Schemnitz, in Hungary, at Freyberg, in Saxony, and elsewhere.

Some few months before these studies were completed Fausto married Juana de Raab, a member of a distinguished Viennese family, and it is a tribute to his standing even at that time that the Spanish ambassador was present at the wedding. It is tempting to surmise that it was something more than a coincidence that another Viennese lady, an ardent and knowledgeable collector of minerals and fossils, also bore the name of De Raab. The collection of Eleonore de Raab was described and catalogued by Ignaz von Born, the catalogue being published in 1790, and it is not impossible that Don Fausto may have assisted in preparing this catalogue and so met not only the owner of the minerals, but other members of her family.

At all events, in June, 1788, Elhuyar sailed from Cadiz on the frigate *Venus*, accompanied by his Juana. Other members of the party included several master miners, three mineralogists, and a mining engineer, all Germans who had contracted to serve in the Spanish colonies for ten years.

In Mexico at that time the mining industry was organized into a Guild, the *Cuerpo de Minería*, the executive governing body of which was known as the *Tribunal de Minería* ; and it was as Director-General of the *Tribunal* that Elhuyar took office. The voyage to Vera Cruz took nearly three months, and the party did not set foot in the New World until 4th September, but no more time was wasted ; on 13th September, 1788, Elhuyar was welcomed in the royal palace at Mexico City by the officers of the *Tribunal*, with appropriate pomp and ceremony.

Elhuyar's first task was to carry out some much-needed reorganization in the administration of the mining industry. When this was completed he was able to turn his energies toward implementing a recommendation that had been made locally some years before, in 1774. This was a proposal that a School of Mines should be established in Mexico. Elhuyar, with his wide experience of similar institutions in Europe, was well qualified to undertake such a project, and he entered on the task with enthusiasm. He prepared a very detailed plan, which he presented to the *Tribunal* in January, 1790, and the School was

actually opened on 1st January, 1792. Not unnaturally it met with some difficulties during its early years, not the least being the slow arrival of equipment from Europe. According to the plan presented by Elhuyar to the *Tribunal*, the preliminary course was to be a four-year one for students aged from fifteen to not more than twenty. The first year was to be devoted to mathematics, the second to the practical applications of geometry to mining problems, and to dynamics and hydrodynamics. In the third year chemistry, mineralogy, and metallurgy were to be the main subjects, as well as what we should now call crystallography; the fourth year was to include studies in "subterranean physics, or the theory of mountains" (a subject perhaps best rendered into modern terms as structural geology), and its applications in all stages of mining practice from prospecting to the extraction of the ore. Drawing was an additional subject, and the study of French was recommended so that the students might extend their knowledge by further reading. The school itself was to be equipped with all necessary laboratories, instruments, and models necessary for efficient teaching.

In actual practice the courses pursued by the students seem to have followed very closely the proposals made by Elhuyar, although certain modifications proved necessary. Advanced mathematics was postponed to the second year, and French was begun in this year. Geology was taught with mineralogy in the third year and chemistry and metallurgy in the fourth. The four-year course was followed by two more years spent studying practical mining in one of several different centres. After this the students returned to Mexico City to present a dissertation and take their final examinations.

The School was maintained from the Guild's Mining Fund, the income of which was provided by the deduction of a fixed percentage from the value of all silver mined in the country. Provision was made for the full maintenance and tuition of twenty-five students, all dependents or close relatives of miners, with preference for the poorest. Paying students were also accepted.

There were various delays, and it was January, 1801, before the first ten students presented their dissertations and received their degrees. From this time onward the school seems to have prospered. Some of the students became assistants to the professors and later became professors themselves. In 1803 the school was honoured by a visit from Baron von Humboldt, who actually took part in examining the students that year. In his "Political Essay on New Spain" Humboldt reported very favourably on the School of Mines "directed by the learned Elhuyar"; and remarked that "no city of the new continent, without excepting those of the United States, presents scientific establishments so large and substantial as the City of Mexico".

Whilst visiting the school Humboldt was able to renew acquaintance

with a former fellow student at Freyberg, Andrés Manuel del Río, now the Professor of Mineralogy. Two years before, Del Río had discovered what he believed to be a new metal in a brown lead ore now known as vanadinite, and he gave details of his analysis to Humboldt for transmission to Europe. Unfortunately owing to various circumstances the significance of his discovery, the metal now known as vanadium, was not realized until some thirty years later.

The revolution that broke out in Mexico in 1810 did not seriously affect the school, although three former students were executed for taking part in the rising. Nevertheless, the internal disorders that followed caused a reduction in the number of students ; and in 1813 the *Tribunal* petitioned unsuccessfully for exemption of the students from military service.

In 1811 the school had moved into a magnificent new building, built in neo-classical style and designed by Manuel Tolsá, an architect and sculptor who was Spanish by birth but who settled in Mexico and carried out important work there. This building, now known as El Palacio de Minería, stands in the street now called Tacuba, near the General Post Office, and is occupied by the School of Engineering of the University.

Although himself Director of the School of Mines, Elhuyar found time for many other activities, visiting mining centres and preparing two valuable reports, one being a detailed study of the history of the coinage of New Spain, published in Madrid in 1818, the other a valuable memoir on the " Influence of Mining on the Agriculture, Industry, Population, and Civilization of New Spain ", published in 1825, also in Madrid.

In 1821 Mexico's struggle to achieve separation from Spain was resolved by the setting up of an independent government. Elhuyar, remaining loyal to Spain, resigned his official appointments in Mexico and returned to Madrid, where in 1822, at the age of sixty-seven, we find him petitioning for a pension and an appointment under the crown. Although at this time disorder and even anarchy were rife in Spain, his capabilities and past services had not been forgotten. He received first an administrative appointment ; followed by a commission to prepare reports on various Spanish mines, including those of Rio Tinto, the mercury mines of Almaden, and the silver mines of Guadalcanal. His report on the Rio Tinto mines was published many years after his death in Volume V of the *Revista Minera* in 1854. Elhuyar also prepared a memoir which formed the basis of the new Spanish mining code known as the " Royal Decree of 1825 ". It was this work which earned him the title of " Father of Spanish Mining Legislation " ; and in 1826 he was made Director-General of Mines, a new post that had been created for him. His experience in Mexico was also utilized in the

planning of a School of Mining Engineering to be established in Madrid. History repeated itself and as a preliminary to starting the school suitable men were sent to study at Freyberg, where Elhuyar himself had studied some fifty years before under very similar circumstances.

Don Fausto de Elhuyar died on 6th January, 1833, in his seventy-eighth year, and so did not live to see the Madrid School opened in 1836. Still active at the time of his death, he had led a full life as a scientist, technologist, teacher, and administrator; and most of his career had been passed in state service. It is not surprising that his memory and achievements are held in high esteem in his native Spain. The centenary of his death was commemorated there in 1933 at a joint meeting of several scientific societies, during which laudatory addresses on the several phases of his career were delivered. The occasion was also marked by the publication of a well documented and detailed biographical account of Elhuyar, prepared by A. de Gálvez-Cañero. A valuable account of the School of Mines in Mexico, together with many details of the mining industry there, was published recently by Walter Howe, and the building in which the school was housed has been described by Justino Fernandez.

I should like to express my indebtedness to Professor José M. Ríos, of Madrid, and the librarian of the Hispanic Council, Canning House, London, for their assistance in obtaining literature.

REFERENCES

FERNANDEZ, J., 1951. El Palacio de Minería. *Ediciones del IV Centenario de la Universidad de México*, iv, Mexico City.

GÁLVEZ-CAÑERO, A. DE, 1933. Apuntes Biográficos de D. Fausto de Elhuyar y de Zubice. *Bol. Inst. y Min. de España*, liii, 377–629, Madrid.

HOWE, W., 1949. *The Mining Guild of New Spain and its Tribunal General, 1777–1821*. Harvard Univ. Press, Cambridge, U.S.A.

C/O BARCLAY'S BANK,
191 EARL'S COURT ROAD,
LONDON, S.W. 5.

CORRESPONDENCE

THE PALAEOZOIC CORAL GENERA *DEPASOPHYLLUM* YÜ AND *DEPASOPHYLLUM* GRABAU

SIR,—Before Dr. Stanley Smith's death last summer, we had completed for publication two papers on our joint work on certain Palaeozoic corals, as well as a note on *Depasophyllum*. I quote the latter in the form in which we had written it:—

" We should like to clear up some misconceptions concerning the generic name *Depasophyllum* applied to Palaeozoic corals. Grabau [*Palaeont. Sinica*, B, ii (1), 1922, pp. 21, 22] introduced the name for Devonian aulate corals, but the name was a *nomen nudum*. It was not till 1936 [*Palaeont. Sinica*, B, viii (4), p. 43] that he diagnosed his genus and described a species (p. 44) under that generic designation, namely, *D. adnetum* Grabau (Middle Devonian, Traverse Group of Michigan, and Onondaga Limestone of New York).

" In the meantime, Yü [*Palaeont. Sinica*, B, xii (3), 1934 (for 1933)] had described and figured two Chinese Carboniferous corals as *Diphyphyllum* (*Depasophyllum*) *convexum* Yü (op. cit., p. 85, pl. 15, fig. 4. Carboniferous, Viséan, Shangssu Limestone; 1 li S.E. of Ti-wu-chung, Ting-fan-hsien, Kueichou, China) and *Diphyphyllum* (*Depasophyllum*) *hochangpingense* Yü (op. cit., p. 86, pl. 16, figs. 5a–d, 6a–b. Carboniferous, Viséan, Tzemenchiao Limestone; Ho-chang-ping, Pao-ching-hsien, Hunan, and 1 li W. of Lan-mu-chiao, Ting-fan-hsien, Kueichou, China). *Depasophyllum* was thus validated by Yü, and this antedates *Depasophyllum* Grabau, 1936.

" *We here select as type-species* of *Depasophyllum* Yü *Diphyphyllum* (*Depasophyllum*) *hochangpingense* Yü. Both that species and the other genosyntype, *Diph.* (*Dep.*) *convexum* Yü, are diphymorphs of *Lithostrotion* Fleming, of which genus *Depasophyllum* Yü is a junior synonym.

" Lang, Smith, and Thomas [*Index of Palaeozoic Coral Genera*, Brit. Mus. (Nat. Hist.), 1940, p. 50] and Stumm (*Mem. Geol. Soc. Amer.*, xl, 1949, p. 30) overlooked Yü and considered *Depasophyllum* Grabau, 1936, valid, citing as type species *D. adnetum* Grabau. Grabau gave no figure of the coral in 1936, but a specimen from the Middle Devonian, Traverse Group, Dock Street Clay, of Alpena, Michigan, U.S.A., was figured by Stumm (op. cit., pl. 14, figs. 20, 21). The species has the generic characters of *Amplexicarinia* (as *Amplexocarinia*) Soshkina (*Bull. Soc. Nat. Moscou, Sect. Géol.*, N.S., xxxvi, 1928, p. 379), of which genus *Depasophyllum* Grabau *non* Yü is thus a junior synonym."

H. DIGHTON THOMAS.

DEPARTMENT OF GEOLOGY,
BRITISH MUSEUM (NATURAL HISTORY),
CROMWELL ROAD,
LONDON, S.W. 7.
1st February, 1956.

TILLITE-GRANITE TRANSFORMATIONS

SIR,—I shall be grateful for the opportunity of commenting on the paper, in the last issue of the *Geological Magazine*, concerning the tillite-granite transformations at Mount Fitton (Chinner, G. A., M. Sando, and A. J. R. White, *Geol. Mag.*, 1956, xciii, 18). The authors appear to have examined only parts of the area and, in consequence, their observations have been confined to localized aspects. Broader considerations, are, however, more relevant to the discussion.

The key to the postulation of post-Adelaide System migmatization (Bowes, D. R., *Univ. Adelaide, Sir Douglas Mawson Anniversary Vol.*, 1952, 7; *Trans. Roy. Soc. S. Aust.*, 1953, lxxvi, 85; *Quart. Journ. Geol. Soc.*, 1954, cix (for 1953), 455) is the age of the relics in the migmatite complexes. The relict sedimentary masses mapped—essentially quartzites, slates, tillites, and marbles and their sheared equivalents—correspond in type and petrographic

characters to the rocks of the Tillite Series of the Adelaide System. They also show a ghost structural pattern apparently similar to that of the Tillite Series and there is no evidence to suggest tight in-folding. On these grounds the relics were reasonably assigned to the Tillite Series and the migmatization was postulated to be post-Adelaide System in age. Further, the Terrapinna Migmatite Complex " is the northerly continuation of the Mount Painter igneous complex " (Sprigg, R. C., *Geol. Surv. S. Aust. Bull.*, xxvi, 1951, 76), which is accepted as resulting from post-Adelaide System granitization and igneous intrusion (Sprigg, R. C., *Geol. Surv. S. Aust. Unpublished Report*, 1945; op. cit., 1951; Sullivan, C. J., *Econ. Geol.*, 1948, xliii, 471; Dickinson, S. B., M. L. Wade, and B. P. Webb, *Geol. Surv. S. Aust. Bull.*, xxx, 1954, 84). It is possible that an older complex, as well as the Adelaide System, was involved in the migmatization (Dickinson, Webb, and Wade, op. cit.), but it is well established that the granitization processes affected considerable areas of the North-Eastern Flinders Ranges and altered sediments of the Adelaide System in situ. In this respect the reference of Chinner, Sando, and White (op. cit., p. 22) to " post-Sturtian metamorphism " in the Mount Painter–Mount Fitton area, without mention of this migmatization and granitization, is misleading.

It appears unlikely that conclusive evidence will be obtained from a study of localized aspects. However, it should be pointed out that the boulders figured by Chinner, Sando, and White (op. cit., Plate II) are uncommon. Had they been derived from an immediately underlying complex, one would expect to find them in abundance, as is the case with the granite boulders in the basal tillite resting on granite at Poolamacca, Broken Hill, N.S.W. (Bowes, D. R., *Trans. Roy. Soc. S. Aust.*, lxxix, 1956). Textural evidence provides considerable difficulties in interpretation, but the presence—not in a boulder—of large quartz-feldspar intergrowths (*vide* Bowes, op. cit., 1954, Plate XXIV, fig. 3) would be difficult to explain by the clastic origin postulated by Chinner, Sando, and White (op. cit., p. 20) for the rocks of the tranisition zone. The marking in of a white line around the feldspar individual (Chinner, Sando, and White, op. cit., Plate III, fig. 1), gives a false impression of the sharpness of the boundary and, further, the line obscures places where there is no break between the fine-grained inclusions in the feldspar and the fine-grained quartz-biotite matrix. Such lines could probably be as well drawn in a number of places within the feldspar individual to give the impression of fragments. The textures shown in figs. 2 and 3 of the same plate are such as would be expected from the migmatization of tillites and similar rocks.

Knowledge of the geology of the North-Eastern Flinders Ranges is still very limited and many problems of great interest and importance remain to be solved. It is hoped that the foregoing comments will be of assistance both in the search for methods of tackling the problems and in the elucidation of the geological history of the area.

D. R. Bowes.

Department of Geology,
University College of Swansea.
9th March, 1956.

REVIEWS

Das Quartär der Lavante, Teil II. Die Entstehung der Ägyptischen Oasendepressionen. By Max Pfannenstiel. Abh. M.-N. Kl. Akad. Wiss. Lit. Mainz, Jahrg. 1953, no. 7, pp. 337–411. Wiesbaden, 1954.

It takes a brave man to enter the geological and geomorphological battlefield of the Egyptian oasis depressions. Dr. Pfannenstiel is armed with a deep and critical reading of the literature and emerges with a brilliant and well-balanced synthesis of the geological history of the whole region from the beginning of the Tertiary to the present day.

He shows how the depressions are overdeepened parts of the normal hollows eroded in the soft beds of a gently tilted scarpland topography, how the depth to which they are eroded has been governed by aridity of climate and level of water-table, and how their sites are often determined ultimately by the occurrence of very gentle tectonic folds, which have promoted more rapid stripping of hard beds in some places than in others. An age-sequence is discerned, from south to north. While the northern Wadi Natrun is eroded in Pliocene and Plio-Pleistocene deposits, and therefore cannot be older than Pleistocene (Günz-Mindel ?), the most southerly oases of Dunkul, Kurkur, Kharga and Dakhla may have been initiated by erosion between the Cretaceous and Eocene; a hollow so formed was probably occupied and enlarged, according to Ball, by a Pliocene tributary of the Nile. In between, the Fayum and Rayan are on the site of a valley excavated by the Oligocene " Urnil ", and although the hollow was completely filled up again, the filling was softer than the surrounding rocks and determined the site of the depression.

Dr. Pfannenstiel grasps the nettle of the Plio-Pleistocene igneous-gravel terrace outliers that cap the watershed west of the pyramids of Giza at heights up to 250 m. above the sea, and does not flinch at the conclusion that the Nile flowed at such heights over what is now the Fayum depression. It was this conclusion that those who discovered and mapped the outliers found so nearly incredible that they marked them on their map with a feeling almost of guilt. For all heights above about 200 m. temporary downwarping of the delta region seems almost a necessity.

The production of the Hawara Channel is attributed to wind acting on soft beds along a line of minor tectonic weakness during and after the period of the Lower Palaeolithic (Mindel-Riss ?) Rus Channel of the Nile; and the Nile and Fayum lake first became connected through the wind-eroded channel in the Riss-Würm interglacial. The connexion was severed during the Würm glaciation when the Nile overdeepened its bed, but re-established when the Nile reaggraded as the result of the Flandrian transgression.

Two works of first importance which appear to have been overlooked, or not received in time to be considered, are Miss Caton-Thompson's monograph on Kharga Oasis (London, 1952) and G. W. Murray's paper on the history of Egyptian climate (*Geogr. Journ.*, 1951). W. J. A.

NEW ZEALAND GEOMORPHOLOGY. By C. A. COTTON. 281 pp., with numerous text-figs. and 16 pls. New Zealand University Press, Wellington, 1955; Cambridge University Press, 1956, price 50*s*.

This book consists of a reprint in chronological order of sixteen of Professor Cotton's early papers, dating from 1912. Taken together, these represent the basis of his book *Geomorphology of New Zealand*, published in 1922. They are here republished, annotated with some author's corrections and additional notes in parenthesis, by the University of New Zealand Press for Victoria University College as a tribute to Professor Cotton, who was for forty-five years head of the Department of Geology. The text is illustrated by the original drawings; sixteen plates of photographs, mostly low-level oblique aerial photos, have been added at the end; and there is a seven-page index.

O. M. B. B.

SOME FUNDAMENTALS OF PETROLEUM GEOLOGY. G. D. HOBSON. Oxford University Press, 1954. pp. 139 + 41 text-figs. Price 18*s*.

GEOLOGY OF PETROLEUM. A. I. LEVORSEN. pp. 703 + 327 illustrations and 47 tables. W. H. Freeman and Co., San Francisco, 1954. (Bailey Bros. and Swinfen, London.) Price 68*s*.

These two books can be thoroughly recommended to anyone with a background of academic geology who wishes to obtain an up-to-date appreciation of the special problems which make up what is usually called " petroleum

geology " (which Levorsen so correctly observes is really only the application of geological principles to the special problems of the oil industry). Both books stress that the particular concern of the oil geologist is the behaviour of fluids, i.e. oil, water, or gas, in rocks. Hobson's little book is a useful summary of the fundamentals on which so much of modern oil exploration and exploitation technology depends; it should be welcomed within the industry, and by students outside, because its subject matter has not previously been made available so conveniently at such a reasonable cost. Levorsen's book is a more comprehensive (and much more expensive) account of the use of geology in the oil industry, with the emphasis on exploration. Written with the benefit of many years' experience in the industry, and in academic work, it qualifies admirably as the one modern text-book on the geology of oil which any oil geologist, or other interested professional man within the industry, should have on his shelves. The writer would draw attention to the philosophical trends of thought expressed in the introductory and final chapters of Levorsen's book, where the relative importance of the various tools available for the business of oil exploration and exploitation are so clearly explained. The danger inherent in the ever more extensive use of modern physical aids is that their users become so engrossed in the fascinating intricacies of their techniques that they sometimes forget that the sediments under investigation were not mass produced in a standardized workshop.

N. L. F.

GEOLOGIE VON SÜDAMERIKA. 2 Band : DER GEOLOGISCHE BAU DER SÜDAMERIKANISCHEN KORDILLERE. By H. GERTH. 244 pp. + 62 figs, 26 pls. Gebrüder Borntraeger. Berlin, 1955. DM. 52.50.

Geologie Südamerikas by the same author was published in three parts in the series : *Geologie der Erde.* That was a stratigraphical study of the continent : Part I up to the end of the Palaeozoic (published in 1932), Part II the Mesozoic (in 1935), and Part III bringing the stratigraphical treatment to a close (in 1942). The present work is regarded as the second volume of the above, though it serves equally well as a second edition of the author's " *Die Kordilleren von Sudamerika* " 1939 which was Part IV.b.2 in the series *Regionalen Geologie der Erde.*

Whereas the arrangement of the two earlier works was primarily stratigraphical with regional subdivisions, the whole plan of the present study is to present a regional tectonic analysis and this gives a more comprehensive and up to date view than anything published since the war. It also contains within it sufficient stratigraphical information to supersede much of the earlier publications—indeed this is intentional so far as Vol. I, Part III, is concerned, for nearly the whole of it was destroyed in Berlin during the War and is virtually unobtainable.

Most of the book deals with the separate tectonic units which make up the Andes. They are grouped into four unequal chapters : the Antarctic, south central, north central, and Caribbean Andes, respectively. Chapter 5 treats the igneous aspects of the structural evolution and is more speculative. The final chapter gives a general summary. Each division is followed by a separate short list of up to date references and there is a geographical and stratigraphical index at the end. The book is well illustrated by numerous sections and diagrammatic maps ; there are three folding tables with stratigraphical summaries of sedimentary, tectonic, and igneous events in sample areas. Perhaps the most striking feature is the collection of twenty loose block diagrams which when assembled give a geological map of the whole region with representative cross sections. This operation needs a large table and is complicated by five variations of the conventions, but it is worth the effort.

This book will for long remain the definitive work on the South American Cordillera and the author is to be congratulated on setting his seal to a lifetime's study of a continent and its great mountain chains.

W. B. H.

UNIVERSITY OF WESTERN AUSTRALIA

Applications are invited for a SENIOR LECTURERSHIP IN ECONOMIC GEOLOGY. Applicants should hold a degree in Science or Engineering, with Geology as a major subject, and have had field experience in Mining and/or Engineering Geology. Experience in Mineragraphy and/or Geophysical Exploration would be an advantage.

The salary range for Senior Lecturers is £A1,597–£A1,937 per annum, and the commencing salary will be determined on the basis of the qualifications and experience of the appointee.

An allowance is made towards travelling expenses.

Further particulars and information as to the method of application may be obtained from the Secretary, Association of Universities of the British Commonwealth, 36 Gordon Square, London, W.C. 1.

The closing date for the receipt of applications, in Australia and London, is *1st June, 1956.*

GOVERNMENT OF CYPRUS

(1) Geologist Class I
and (2) Geologist Class II
Water Development Department

Qualifications : (1) and (2). Good honours geology degree and (1) not less than 10 years' experience in geology including water geology and drilling ; (2) several years' experience of practical geological work.

Age limits: (1) 30–40 years.
(2) 25–35 years.

Duties : (1) and (2). Siting prospecting and production bore-holes ; supervising drilling and pump testing operations ; making geophysical surveys for water.

Terms of Appointment : (1) and (2). On contract/gratuity terms for 4 years, with emoluments in the scale (1) £1,480–£1,857 per annum ; (2) £1,080–£1,440 per annum. (1) and (2). Cost of living allowance ; gratuity on satisfactory completion of contract ; outfit allowance £30 ; free passages ; Government quarters at rental ; generous leave ; income tax at local rates.

Apply to Director of Recruitment, Colonial Office, London, S.W. 1, state age, briefly qualifications, and experience. Quote BCD. 140/17/04.

TOPOGRAPHER required by UGANDA GOVERNMENT Geological Survey Department on probation for pensionable employment. Salary scale (including Inducement Pay and present temporary allowance of 10 per cent of salary), £772, rising to £1,280 a year. Commencing salary according to qualifications and experience. Outfit allowance up to £30. Free passages. Liberal leave on full salary. Candidates, male, not over 35 and preferably single, must have experience of topographical surveying, particularly in the use of the plane-table, theodolite, and dumpy level. Experience in water development projects with particular reference to all aspects of construction and survey of earth embankments would be an advantage. Write to the Crown Agents, 4 Millbank, London, S.W. 1. State age, name in block letters, full qualifications, and experience and quote M3B/35484/GV.

The Geological Magazine

Bound volumes are better than loose parts. Send your *Geological Magazine* to be bound in attractive green cloth covers, 15/– (postage 1/3 extra); cloth cases only, 5s. 3d. (postage 5d. extra).

STEPHEN AUSTIN & SONS, LTD.
CAXTON HILL, WARE ROAD, HERTFORD

EDWARD ARNOLD

THE COALFIELDS OF GREAT BRITAIN
Edited by
SIR ARTHUR TRUEMAN, K.B.E., D.Sc., F.R.S.
408 pages 113 illustrations 63*s*. net

COAL: ITS FORMATION AND COMPOSITION
W. FRANCIS, M.Sc. Tech., Ph.D., F.R.I.C., F.Inst.F.
575 pages 204 illustrations 133 tables 84*s*. net

THE USE OF STEREOGRAPHIC PROJECTION IN STRUCTURAL GEOLOGY
F. C. PHILLIPS, M.A.
94 pages 95 diagrams 15*s*. net.

THE GEOLOGY OF THE COMMONWEALTH OF AUSTRALIA
The late SIR T. W. EDGEWORTH DAVID, F.R.S.
In 3 volumes: Fully illustrated with maps, sections and plates
£12 12*s*. net.
The geological map of New Guinea is obtainable separately price 6*s*.
(by post 2*s*. 1*d*. extra)

41 MADDOX STREET, LONDON, W. 1.